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	Engineering and Design PAINTING: NEW CONSTRUCTION AND MAINTENANCE	
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**US Army Corps
of Engineers**

EM 1110-2-3400
30 April 1995

ENGINEERING AND DESIGN

Painting: New Construction and Maintenance

ENGINEER MANUAL

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CECW-EE

**DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000**

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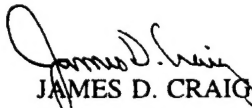
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**Engineering and Design
PAINTING: NEW CONSTRUCTION AND MAINTENANCE**

1. Purpose. This manual provides painting guidance to engineering, operations, maintenance, and construction personnel and other individuals responsible for the protection of U.S. Army Corps of Engineers (USACE) structures. It gives broad-base instructions on corrosion and corrosion protection using protective coating and state-of-the-art procedures that can be employed on Corps projects, which can aid in attaining better and, from a long-range viewpoint, more economical paint jobs.

2. Applicability. This EM applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having responsibilities for the design and construction of civil works projects.

FOR THE COMMANDER:


JAMES D. CRAIG
Colonel, Corps of Engineers
Chief of Staff

CECW-EE

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Chapter 1 Introduction

1-1. Purpose

This manual provides painting guidance to engineering, operations, maintenance, and construction personnel and other individuals responsible for the protection of U.S. Army Corps of Engineers (USACE) structures. It gives broad-base instructions on corrosion and corrosion protection using protective coating and state-of-the-art procedures that can be employed on Corps projects, which can aid in attaining better and, from a long-range viewpoint, more economical paint jobs.

1-2. Applicability

This EM applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having responsibilities for the design and construction of civil works projects.

1-3. References

Required and related references are listed in Appendix A.

1-4. Abbreviations and Acronyms

Abbreviations and acronyms used herein are explained in Appendix B.

1-5. Neutral Language Use and Terms

a. Throughout this manual neutral language is used to include both masculine and feminine genders; any exceptions to this statement will be noted.

b. The words "paint," "painting," and "coating" are used broadly herein to indicate all common types of protective and decorative coatings, applied hot or cold, by brush, roller, spray, and other means.

1-6. Scope

a. Although this manual is not intended to be a general textbook on coatings and coatings application, the complexity of the modern coatings field justifies something more than a bare, utilitarian approach to the presentation of useful information. Therefore, moderately detailed discussions of coating materials and characteristics of applied coating systems are included, even though their immediate usefulness may not be apparent to those who are interested only in "practical" information. Presumably,

acquiring this additional knowledge will help personnel responsible for painting of civil works structures.

b. Little distinction is made between contract and hired-labor painting. When such subjects as selection of surface preparation and coating application equipment (Chapters 7 and 8, respectively) are discussed, it is recognized that the information may not be directly applicable to contract work for which the end result is specified rather than the means to that end. However, the information will provide a valuable background for those who inspect and administer contract painting work.

c. Certain classes of coatings systems are discussed in the manual even though they do not appear in CWGS 09940 and CEGS-09900. Some of these coating systems are included for general familiarization; others are included because they may be considered for adoption as standard painting schemes.

d. Materials such as galvanizing, metallizing, and protective tapes are discussed even though they are not commonly considered paints or coatings. The inclusion of these subjects illustrates that the protection of metal surfaces cannot logically be divided into precise, independent subjects.

e. Because this manual will be used extensively as a reference it includes a complete topic index to facilitate locating specific information. Appendix A will help locate references to particular standard specifications.

1-7. Painting for Corrosion Protection and Aesthetics

Protection and the appearance (aesthetics) of surfaces are among the most important elements of the maintenance costs of civil works projects, particularly those with large areas of exposed steel. The protection problem may become evident even in the design stage; the engineer may overdesign to provide a safety factor against the corrosion that may take place in the future. Inadequate control of metal corrosion results in an economic loss of millions of dollars annually. Conservation of natural resources requires that the unnecessary and inexcusable waste of materials through inadequate protection be prohibited. Exorbitantly high standards of protection and appearance also are unjustifiably expensive. A principal means of preventing deterioration is the use of paint coatings. The paint industry has made important progress in improving protective coatings. The prompt adoption and proper use of these improved materials can be expected of those responsible for the protection and appearance of costly structures. The time has passed when an oil-base (alkyd) coating could be

applied, regardless of surface characteristics and exposure conditions. The present-day complexity of materials available in the coating field requires that engineers devote more study to the subject. The advent of regulations for volatile organic compounds (VOCs) as well as regulations for the removal of lead coatings from industrial structures has drastically changed the way the industry is using coatings for corrosion protection. Local organizations are not encouraged to conduct paint evaluation programs of their own; these programs may not be useful and can be misleading unless carried out carefully and under controlled conditions that permit side-by-side comparisons with coatings of known capabilities. In connection with improvement of painting operations, it would be worthwhile for each district to designate an engineer from within the existing organization to act as an adviser on matters relating to paints and painting. The duties of this employee, probably in conjunction with other work, would include:

- a.* Keeping informed on the specifications, manuals, and other directives on paints and painting disseminated by USACE and other Government agencies.
- b.* Advising other interested members of the organization on matters related to protective coatings.
- c.* Assisting in the preparation of specifications for paint procurement and contract or hired-labor painting.
- d.* Assisting in the selection of paints for specific jobs.
- e.* Providing technical guidance on maintenance painting operations.
- f.* Ensuring the adequacy of inspection of painting operations.
- g.* Retaining paint service records.
- h.* Remaining current with governing Occupational Safety and Health Administration (OSHA) regulations as well as current environmental protection laws related to surface preparation and painting operations.

Chapter 2 Corrosion Theory and Corrosion Protection

2-1. Introduction

a. The annual cost of corrosion and corrosion protection in the United States is estimated by the National Association of Corrosion Engineers (NACE) to be in excess of 10 billion dollars. This figure is perhaps less intimidating considering that corrosion occurs, with varying degrees and types of degradation, whenever metallics are used.

b. Corrosion can be mitigated by five basic methods: coatings, cathodic protection, materials selection, chemical inhibitors, and environmental change. A basic understanding of corrosion will enable USACE personnel to comprehend how these methods help prevent corrosion, and it will establish an overall introduction to the purpose for the entire engineer manual on painting.

2-2. Causes of Corrosion

Corrosion is defined as the deterioration of a material, usually a metal, because of a reaction with its environment and which requires the presence of an anode, a cathode, an electrolyte, and an electrical circuit. To understand the application of protective coatings or cathodic protection in corrosion control, the basic concepts of corrosion of metals in the presence of moisture needs to be reviewed.

a. Corrosion occurs by an electrochemical process. The phenomenon is similar to that which takes place when a carbon-zinc "dry" cell generates a direct current. Basically, an anode (negative electrode), a cathode (positive electrode), an electrolyte (environment), and a circuit connecting the anode and the cathode are required for corrosion to occur (see Figure 2-1). Dissolution of metal occurs at the anode where the corrosion current enters the electrolyte and flows to the cathode. The general reaction (reactions, if an alloy is involved) that occurs at the anode is the dissolution of metal as ions:



where

M = metal involved

n = valence of the corroding metal species

e = electrons

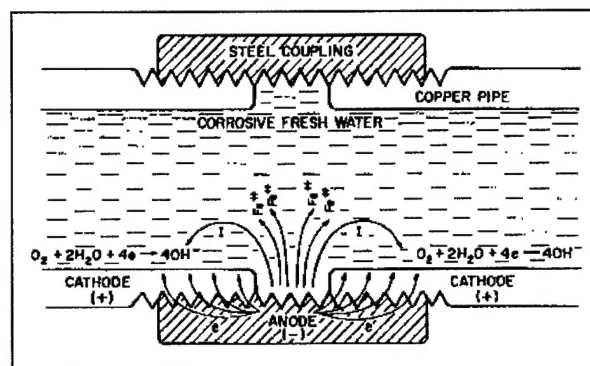
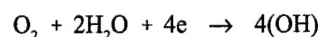
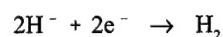


Figure 2-1. The basic corrosion cell consists of an anode, a cathode, an electrolyte, and a metallic path for electron flow. Note that the corrosion current (I) enters the electrolyte at the anode and flows to the cathode

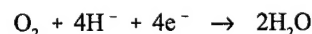
Examination of this basic reaction reveals that a loss of electrons, or oxidation, occurs at the anode. Electrons lost at the anode flow through the metallic circuit to the cathode and permit a cathodic reaction (or reactions) to occur. In alkaline and neutral aerated solutions, the predominant cathodic reaction is



The cathodic reaction that usually occurs in deaerated acids is



In aerated acids, the cathodic reaction could be

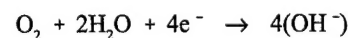


All of these reactions involve a gain of electrons and a reduction process.

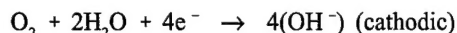
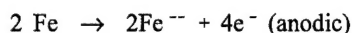
b. The number of electrons lost at the anode must equal the number of electrons gained at the cathode. For example, if iron (Fe) was exposed to an aerated, corrosive water, the anodic reaction would be



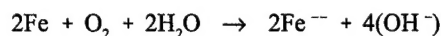
At the cathode, reduction of oxygen would occur



Because there can be no net gain or loss of electrons, two atoms of iron must dissolve to provide the four electrons required at the cathode. Thus, the anodic and cathodic reactions would be



These can be summed to give the overall oxidation-reduction reaction



c. After dissolution, ferrous ions (Fe^{++}) generally oxidize to ferric ions (Fe^{+++}); these will combine with hydroxide ions (OH^{-}) formed at the cathode to give a corrosion product called rust (FeOOH or $\text{Fe}_2\text{O}_3 \cdot x \text{H}_2\text{O}$). Similarly, zinc corroding in an aerated, corrosive water (i.e., $\text{Zn} \rightarrow \text{Zn}^{++} + 2\text{e}^{-}$) will form the corrosion product $\text{Zn}(\text{OH})_2$. The important issue to remember is that anodic dissolution of metal occurs electrochemically; the insoluble corrosion products are formed by a secondary chemical reaction.

2-3. Forms of Corrosion

Almost all corrosion problems and failures encountered in service can be associated with one or more of the eight basic forms of corrosion: general corrosion, galvanic corrosion, concentration-cell (crevice) corrosion, pitting corrosion, intergranular corrosion, stress corrosion cracking, dealloying, and erosion corrosion.

a. *General corrosion.* With general corrosion (sometimes called uniform corrosion), anodic dissolution is uniformly distributed over the entire metallic surface. The corrosion rate is nearly constant at all locations. Microscopic anodes and cathodes are continuously changing their electrochemical behavior from anode to cathode cells for a uniform attack. The general corrosion rates for metals in a wide variety of environments are known, and common practice is to select materials with rates that are acceptable for the application.

b. Galvanic corrosion.

(1) Galvanic (dissimilar metals) corrosion occurs when two electrochemically dissimilar metals are metallogically connected and exposed to a corrosive environment. The less noble metal (anode) suffers accelerated attack and the more noble metal (cathode) is cathodically protected by the galvanic current. The tendency of a metal to corrode in a galvanic cell is determined by its position in the "galvanic series" of metals and alloys as listed in Table 2-1.

Table 2-1
Galvanic Series in Seawater at 25 °C (77 °F)

Corroded end (anodic, or least noble)
Magnesium
Magnesium alloys
Zinc
Galvanized steel or galvanized wrought iron
Aluminum alloys - 5052, 3004, 3003, 1100, 6053, in this order
Low-carbon steel
Wrought iron
Cast iron
Ni-Resist (high-nickel cast iron)
Type 410 stainless steel (active)
50-50 lead-tin solder
Type 450 stainless steel (active)
Type 304 stainless steel (active)
Type 316 stainless steel (active)
Lead
Tin
Copper alloy C28000 (Muntz metal, 60% Cu)
Copper alloy C67500 (manganese bronze)
Copper alloys C46400, C46500, C46600
Alloy 200 (active)
Alloy 6700 (active)
Alloy B
Chlorimet 2
Copper alloy C27000 (yellow brass, 65% Cu)
Copper alloys C44300, C44400, C44500 (admiralty brass)
Copper alloys C60800, C61400 (aluminum bronze)
Copper alloy C23000 (red brass, 85% Cu)
Copper C11000 (ETP copper)
Copper alloys C65100, C65500 (silicon bronze)
Copper alloy C71500 (copper nickel, 30% Ni)
Copper alloy C92300, cast (lead tin bronze G)
Copper alloy C92200, cast (lead tin bronze M)
Alloy 200 (passive)
Alloy 600 (passive)
Alloy 400
Type 410 stainless steel (passive)
Type 304 stainless steel (passive)
Type 316 stainless steel (passive)
Alloy 825
Alloy 62
Alloy C
Chlorimet 3
Silver
Titanium
Graphite
Gold
Platinum
Protected end (cathodic, or most noble)

(2) The metal order listed in Table 2-1 is only appropriate for seawater at 25 °C (77 °F). The order may vary with both temperature and composition of the electrolyte (water or soil). In fact, under some conditions, two metals may reverse their water respective order (potentials). For example, iron may become anodic with respect to zinc in fresh water at a temperature above 66 °C (150 °F).

(3) A common galvanic corrosion cell occurs when

copper lines are connected to galvanized steel water mains. In this example, the soil is the electrolyte, the copper line is the cathode, and the water main is the anode.

c. Concentration-cell corrosion. Concentration-cell corrosion occurs because of differences in the environment surrounding the metal. This form of corrosion is sometimes referred to as "crevice corrosion," "gasket corrosion," and "deposit corrosion" because it commonly occurs in localized areas where small volumes of stagnant solution exist. Normal mechanical construction can create crevices at sharp corners, spot welds, lap joints, fasteners, flanged fittings, couplings, threaded joints, and tube sheet supports. At least five types of concentration cells exist; the most common are the "oxygen" and "metal ion" cells. Areas on a surface in contact with an electrolyte having a high oxygen concentration generally will be cathodic relative to those areas where less oxygen is present (oxygen cell). Areas on a surface where the electrolyte contains an appreciable quantity of the metal's ions will be cathodic compared to locations where the metal ion concentration is lower (metal ion cell).

d. Pitting corrosion. Pitting corrosion is a randomly occurring, highly localized form of attack on a metal surface, characterized by the fact that the depth of penetration is much greater than the diameter of the area affected. Pitting is one of the most destructive forms of corrosion, yet its mechanism is not completely understood. Steel and galvanized steel pipes and storage tanks are susceptible to pitting corrosion and tuberculation by many potable waters. Various grades of stainless steel are susceptible to pitting corrosion when exposed to saline environments.

e. Intergranular corrosion. Intergranular corrosion is a localized condition that occurs at, or in narrow zones immediately adjacent to, the grain boundaries of an alloy. Although a number of alloy systems are susceptible to intergranular corrosion, most problems encountered in service involve austenitic stainless steels (such as 304 and 316) and the 2000 and 7000 series aluminum alloys. Welding, stress relief annealing, improper heat treating, or overheating in service generally establish the microscopic, compositional inhomogeneities that make a material susceptible to intergranular corrosion.

f. Stress corrosion cracking. Stress corrosion cracking (environmentally induced-delayed failure) describes the phenomenon that can occur when many alloys are subjected to static, surface tensile stresses and are exposed to certain corrosive environments. Cracks are initiated and propagated by the combined effect of a surface tensile stress and the environment. When stress corrosion cracking occurs, the

tensile stress involved is often much less than the yield strength of the material; the environment is usually one in which the material exhibits good resistance to general corrosion.

g. Dealloying. Dealloying is a corrosion process in which one element is preferentially removed from an alloy. This occurs without appreciable change in the size or shape of the component; but the affected area becomes weak, brittle, and porous. The two most important examples of dealloying are the preferential removal of zinc from copper-zinc alloys (dezincification), and the preferential removal of iron from gray-cast iron (graphitic corrosion). Graphitic corrosion sometimes occurs on underground cast iron water mains and leads to splitting of the pipe when the water pressure is suddenly increased.

h. Erosion corrosion. Erosion corrosion refers to the repetitive formation (a corrosion process) and destruction (a mechanical process) of the metal's protective surface film. This typically occurs in a moving liquid. Erosion may be impinging (in the case of a pipe ell) or sliding (pipe wall) when it occurs. An example is the erosion corrosion of copper water tubes in a hot, high velocity, soft water environment. Cavitation is a special form of erosion corrosion.

2-4. Corrosion Mitigation

Corrosion mitigation can be accomplished by design considerations, by employing corrosion-resistant materials of construction, by employing cathodic protection, by using protective coatings, or by using inhibitors.

a. Design considerations. The use of acceptable engineering practices to minimize corrosion is fundamental to corrosion control. This is accomplished by engineering design. One of the most important factors in designing for corrosion control is to avoid crevices where deposits of water-soluble compounds and moisture can accumulate and are not accessible for maintenance. Any region where two surfaces are loosely joined, or come into proximity, also qualifies as a crevice site. Joining geometries also present various crevice corrosion problems. Examples include: bolting, back-to-back angles, rough welds, weld spatter, sharp edges, corners, discontinuities, and intermittent welding.

(1) Crevice corrosion. Crevice corrosion relies on establishing a crevice geometry to allow water or other liquids or deposits to enter the crevice. One form of corrosion prevention is to eliminate crevice geometry by design. Joints and fastenings should be arranged to give clean, uninterrupted lines; therefore, welded joints are

preferable to bolted or riveted joints. Sound welds and complete weld penetration will help to avoid porosity and crevice development that often result from intermittent welding, rough welds, and weld spatter. Grinding sharp edges, corners, welds, and weld spatter will help prevent crevice corrosion, as well as paint striping procedures over similar surfaces. Striping is a procedure that entails brush or spray application of the primer or, in some instances, the entire coating system over potential corrosion sites. Striping is designed to give additional barrier protection from the exposure, and it is common when the service environment includes some degree of immersion or splash.

(2) Stainless steel coupled to carbon steel. The galvanic series listed in Table 2-1 illustrates some of the common metals in seawater. The further apart the metals are in the series, the more rapid the corrosion of the more anodic metal will be. That is, a metal tends to corrode when connected to a more cathodic metal. For example, carbon steel will corrode more rapidly when connected to stainless steel.

(3) Stainless steel—active and passive states.

(a) Several grades of stainless steel appear toward the anodic (upper) end of the galvanic series when they are in the "active" condition, and at the cathodic (lower) end when they are in the "passive" condition. The corrosion-resistant nature of stainless steel is related to its inherent ability to form a protective oxide film in the presence of oxygen or various oxidizing chemicals such as nitric or sulfuric acid. If the protective oxide film is destroyed, the stainless steel is subjected to rapid corrosion (the active condition) in the presence of oxygen-free acids such as hydrochloric acid. Therefore, the correct application of a specific grade of stainless steel should include a determination if the oxidation level of the environment will result in a passive or active state.

(b) Stainless steels, particularly the 300 series, are subject to a heat treating effect called "sensitization" during welding and stress relieving between 427 °C (800 °F) and 760 °C (1400 °F). During welding, these stainless steels may form chromium carbides (at temperatures of 427 °C (800 °F) to 760 °C (1400 °F)). Therefore, the chromium near the grain boundaries is tied up and no longer forms the protective oxide film (chromium oxide). Thus, the grain boundaries are susceptible to intergranular corrosion and the stainless steel is no longer in the passive state. Sensitized stainless steels can deteriorate in acidic soil or water. This type of corrosion can be prevented by a solution treatment and repassivation process after welding.

(4) Unfavorable area differences. The rate of corrosion resulting from galvanic action frequently will depend on the

relative exposed areas of the two metals in contact. For example, zinc will corrode when connected to iron. The zinc will "protect" the iron by making it the cathode of the galvanic cell. This is the principle behind a zinc-rich coating on steel. Small anode areas, in combination with large cathode areas, should be avoided whenever possible. A small piece of zinc will corrode rapidly when coupled to a large area of iron, yet the iron will receive little protection. Coating less noble metals and leaving the more noble metal uncoated is not recommended. A poor coating application can reduce the service life of the metal significantly because of local defects which will cause accelerated anodic corrosion resulting from a galvanic action. Examples of these coating defects are pinholes, scratches, skips, and physical damage.

(5) Isolation of dissimilar metals. Galvanic attack may be prevented by using an insulator to prevent contact (completion of electrical circuit) between dissimilar metals. The more noble metal can be insulated from the less noble metal through the use of plastic washers for fasteners. Ceramics or nonconductive insulating materials also may be used.

(6) Connection of old and new materials. Galvanic corrosion is not limited to cells in which totally dissimilar metals are in contact and exposed to an electrolyte. Differences in the composition or surface condition of "similar" metals frequently can result in galvanic corrosion cells. For example, clean steel is typically anodic to corroded steel. Therefore, it is common in pipeline operations to find new pipeline installed in a repaired section or branch line corroding more rapidly than the old line to which it is connected. The older pipe causes accelerated corrosion of the new piping because of galvanic action. Local galvanic anode installation or the application of an insulator may prevent this problem.

(7) Electrical grounding. Steel pipe in soil or water, electrically connected to rebar in concrete, is another corrosion-related problem associated with galvanic cells. Steel pipe always should be prevented from contacting the reinforcing steel in concrete because the reinforcing steel is passive and will cause accelerated corrosion of the steel piping.

(8) Galvanized piping in 60 °C (140 °F) to 77 °C (170 °F) water. At normal ambient temperatures, galvanized steel is anodic to unprotected steel. The sacrificial action of the zinc is caused by the relative potential difference of zinc and iron at normal temperatures. However, in hot water applications, the potential of zinc decreases (becomes more cathodic) with an increase in temperature and actually may have the anodes and cathodes reversed. The steel would become anodic to the zinc.

Therefore, galvanized piping should not be used when water immersion temperatures are in the 60 °C (140 °F) to 77 °C (170 °F) range because the steel may become sacrificial to the zinc.

b. Cathodic protection. Cathodic protection is an electrical method of mitigating corrosion on metallic structures that are exposed to electrolytes such as soils and waters. Corrosion control is achieved by forcing a defined quantity of direct current to flow from auxiliary anodes, through the electrolyte, and onto the metal structure to be protected. Theoretically, corrosion of the structure is completely eliminated when the open-circuit potentials of the cathodic sites are polarized to the open-circuit potentials of the anodic sites. The entire protected structure becomes cathodic relative to the auxiliary anodes. Therefore, corrosion of the metal structure will cease when the applied cathodic current equals the corrosion current. There are two basic methods of corrosion control by cathodic protection. One involves the use of current that is produced when two electrochemically dissimilar metals or alloys (Table 2-1) are metallogically connected and exposed to the electrolyte. This is commonly referred to as a sacrificial or galvanic cathodic protection system. The other method of cathodic protection involves the use of a direct current power source and auxiliary anodes, which is commonly referred to as an impressed current cathodic protection system.

(1) Sacrificial (galvanic) systems. Sacrificial-anode-type cathodic protection systems provide cathodic current by galvanic corrosion. The current is generated by metallogically connecting the structure to be protected to a metal/alloy that is electrochemically more active than the material to be protected. Both the structure and the anode must be in contact with the electrolyte. Current discharges from the expendable anode through the electrolyte and onto the structure to be protected. The anode corrodes in the process of providing protection to the structure. The basic components of a single, sacrificial-anode-type cathodic protection installation are the structure to be protected, the anode, and the means of connecting the structure to the anode. This is shown in Figure 2-2.

(a) The cathodic current generated by the sacrificial anode depends on the inherent potential between the anode and the structure to be protected. Theoretically, any metal or alloy more electrochemically active than another would be capable of cathodically protecting the more noble material. In practice, only Type 2 zinc (99.9 percent Zn conforming to ASTM B418) and alloys of magnesium are used for the protection of steel in soils. Although zinc has a higher current output efficiency, most sacrificial anodes installed for the protection of underground steel structures are fabricated from magnesium alloys because magnesium

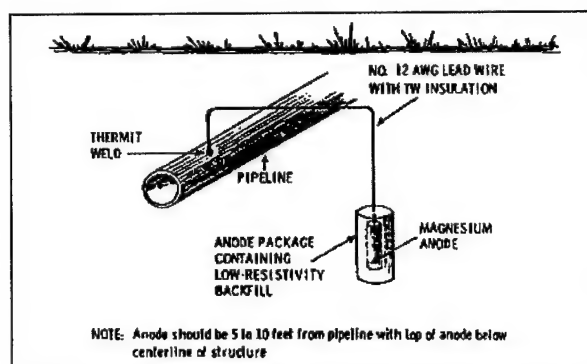


Figure 2-2. Schematic view showing sacrificial-anode-type cathodic protection installation for an underground steel pipeline

alloys provide a higher driving potential.

(b) Sacrificial-anode-type cathodic protection systems have a number of advantages:

- No external power is required
- No regulation is required
- Easy to install
- Minimum of cathodic interference problems
- Anodes can be readily added
- Minimum of maintenance required
- Uniform distribution of current
- Minimum right-of-way/easement costs
- Efficient use of protective current
- Installation can be inexpensive if installed at time of construction

(c) Sacrificial-anode-type systems also have disadvantages that limit their application:

- Limited driving potential
- Lower/limited current output
- Poorly coated structures may require many anodes
- Can be ineffective in high-resistivity environments
- Installation can be expensive if installed after construction

(2) Impressed current systems. Impressed-current-type cathodic protection systems provide cathodic current from an external power source. A direct current (DC) power source forces current to discharge from expendable anodes through the electrolyte and onto the structure to be protected. Although the current is not generated by the corrosion of a sacrificial metal/alloy, the energized materials used for the auxiliary anodes do corrode.

(a) The basic components of an impressed-current-type

cathodic protection system are the structure to be protected, a DC power source, a group of auxiliary anodes (ground bed or anode bed), and insulated lead wires connecting the structure to be protected to the negative terminal of the power source and the ground bed to the positive terminal of the power source. This is shown in Figure 2-3.

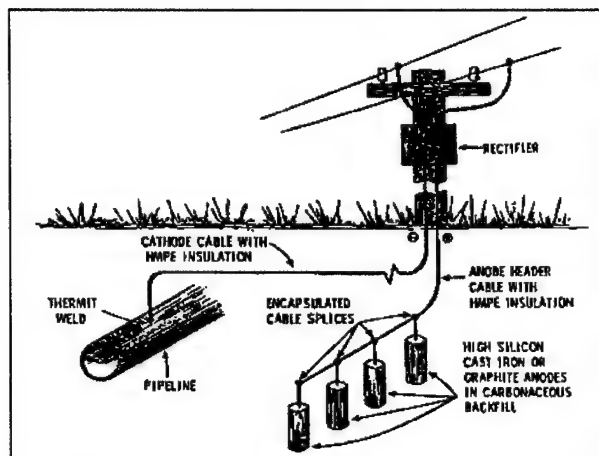


Figure 2-3. Schematic view showing impressed-current-type cathodic protection installation for an underground steel pipeline

(b) The DC power source is usually a rectifier, although current also can be obtained using engine-driven generators, batteries, solar cells, fuel cells, wind-powered generators, and thermoelectric generators. High-silicon chromium-bearing cast iron anodes and ceramic-coated anodes are commonly used materials for auxiliary anodes when impressed-current-type cathodic protection systems are used to mitigate corrosion on underground steel structures.

(c) Impressed-current-type cathodic protection systems have a number of advantages:

- Can be designed for a wide range of voltage and current
- High ampere-year output is available from single ground bed
- Large areas can be protected by single installation
- Variable voltage and current output
- Applicable in high-resistivity environments
- Effective in protecting uncoated and poorly coated structures

(d) Impressed-current-type systems also have disadvantages which limit their application:

- Can cause cathodic interference problems
- Are subject to power failure and vandalism
- Have right-of-way restrictions

- Require periodic inspection and maintenance
- Require external power, resulting in monthly power costs
- Overprotection can cause coating damage

(3) Systematic cathodic protection design procedure. The systematic cathodic protection design procedure provides the corrosion engineer an opportunity to evaluate the technical and economical benefits that result when several cathodic protection system designs are considered for a given project. The engineer is provided an opportunity to select the most advantageous system. Basically, the systematic cathodic protection design procedure is an optimization of the various existing methods. The procedure simultaneously considers both types of cathodic protection systems; it is applicable to both proposed and existing underground structures. Most important, the procedure provides flexibility in evaluating the alternatives, which are available in selecting the optimum cathodic protection system for the structure involved.

(a) During the predesign phase, basic information is obtained regarding the structure and its external environment. This information is collected by conducting and evaluating the results of selected field tests and considering the corrosion-control experience of other operations in the general area. The objective of the predesign phase is to determine the viability of cathodic protection as an effective means of corrosion control.

(b) The design phase sizes the cathodic protection system components. Initial iterations in the design phase, however, should be considered tentative. Once the tentative system components are selected, technical and economical life cycle costs must be calculated. Comparison of the various alternatives then can be made by evaluating each system's technical/economical benefits. Plans and specifications can be developed after design analysis; the system then can be installed. Following installation, the design procedure requires that the corrosion engineer conduct further field surveys to ensure that the protection criterion selected from NACE RP-01-69 is satisfied. The systematic design procedure also requires that, with an impressed-current-type cathodic protection system, additional field tests be conducted to ensure that no stray current corrosion problems exist. The procedure also requires that the corrosion engineer outline a cathodic protection system re-occurring maintenance program. The following publications should be referenced when designing either a sacrificial or impressed-current cathodic protection system: ETL 1110-9-10, ETL 1110-3-440, TM 5-811-7, and CWGS 16643.

(4) Monitoring effectiveness of cathodic protection systems. After a cathodic protection system is installed, the

system needs to be monitored. The system should be evaluated periodically to ensure that it is providing corrosion protection to the metallic structure. Criteria have been developed to determine if adequate corrosion protection is being achieved on the structure in question. For example, some of the indications of a cathodic protection problem include changes in operating conditions of the rectifier output and any noted corrosion increase of the structures.

(5) Criteria for cathodic protection. Structure-to-electrolyte potential measurements are analyzed to determine whether or not a structure is cathodically protected; these measurements are made by the use of cathodic protection criteria. Unfortunately, no one simple criterion has been accepted by all cathodic protection engineers that can be practicably measured in the field under all circumstances. Guidelines for selecting the proper criterion under various circumstances will be provided below. Guidance concerning the criteria of cathodic protection for external corrosion control on underground structures is found in two recommended practices (RP's) published by NACE. These are RP-01-69 and RP-02-85. A summary of the criteria for steel and cast iron structures follows.

(a) One criterion is a negative (cathodic) potential of at least 850 millivolts (mV) with the cathodic protection applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement.

(b) A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode is another criterion. Polarized potential is defined as the potential across the structure/electrolyte interface that is the sum of the corrosion potential and the cathodic polarization.

(c) Another criterion is defined as a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formulation or decay of polarization can be measured to satisfy this criterion. The -0.85 volt (V) potential criterion states that voltage drops other than those across the structure to electrolyte boundary must be considered when interpreting the measurements. Two criteria, "polarization" and "polarized potential," need to be considered. This is of utmost concern when evaluating potential measurements because only polarization provides cathodic protection. No protection is provided by the voltage drops other than those across the structure-to-electrolyte (i.e., structure-to-soil) boundary.

(6) CP diagnostic software. USACERL (U.S. Army Construction Engineering Research Laboratories) has developed a software package called CP Diagnostic that is helpful in evaluating the performance of cathodic protection systems and storing the data necessary to document the performance. The program stores background data about the cathodic protection system and protected structures, as well as all field data collected (including structure-to-soil potentials, anode-to-structure currents, isolation joint test results, and rectifier readings). The program automatically evaluates the structure-to-soil potentials against the criteria of cathodic protection and lists locations where protection is not being achieved. In addition, an expert system module is being developed to assist the field inspector in the troubleshooting of problems by leading the inspector through a series of questions. A diagnosis of the problem is then provided, and a remedy is suggested.

(7) Dielectric isolation. It may be desirable to electrically isolate a cathodically protected structure from all other metallic structures, such as connecting lines, pump stations, terminals, etc. If the installation is not isolated, these connections also will be cathodically protected, and current requirements frequently will be excessive. Electrical insulation of pipelines and other structures is accomplished by dielectric isolation. Small lines may be insulated by insulating couplings or unions. If feasible, insulated flanges should be assembled and electrically tested with an ohmmeter before being connected into a line.

c. Inhibitors. Any substance, when added in small quantities to a corrosive environment containing carbon steel or an alloy that will decrease the corrosion rate is called an inhibitor. Inhibitors function in various ways and are beyond the scope of this manual. Additions of soluble hydroxides, chromates, phosphates, silicates, and carbonates are used to decrease the corrosion rate of carbon steel and alloys in various corrosive environments. The concentration of a given inhibitor needed to protect a metal will depend on a number of factors such as composition of the environment, temperature, velocity of the liquid, the presence or absence in the metal of internal or external stresses, composition of the metal, and the presence of any other metal contact. The type and quantity of inhibitors required for a given metal may be determined by experiments. These experiments should include measurements on the location and degree of corrosive attack as a function of inhibitor type and concentration. Corrosive attacks may occur even if experimentation shows that adequate levels and the correct type of inhibitor are used. Small anode areas and increased attack may develop under loose scale, under deposits of foreign matter, in crevices, and in similar locations relatively inaccessible to the inhibitor.

d. Protective coatings. Coatings and linings play a significant role in corrosion prevention and are used extensively for this purpose. Coatings also can perform other valuable functions such as: provide easier cleanability, decontamination or graffiti removal, add color or a pleasing aesthetic appearance, increase light reflectance for a better working environment or for safety purposes, and provide a color marking or safety warning. There are many different types of coatings. Organic coatings are most commonly applied by brush, roller, or airless or conventionally atomized air-spray equipment. These coatings consist of an organic binder or film former with inhibitive, barrier, and sacrificial pigments for corrosion protection. Because of

the concerns regarding worker and environmental protection, many coating formulations are changing to the use of nontoxic, nonhazardous pigments and/or solvents, using water-based or high-solids binders. Metallic coatings such as thermal sprayed zinc, aluminum or aluminum-zinc alloys, stainless steel, and chromium can be used to protect against corrosion or provide increased wear or abrasion resistance. Zinc-rich coatings are widely used to provide galvanic corrosion protection to steel. Galvanizing (either strip or hot-dip) is another way of applying zinc to a steel surface for corrosion protection. Protective coating types are discussed in detail in Chapter 4.

Chapter 3 Paint Material Specifications, Procurement, and Testing

3-1. Introduction

This chapter is intended to provide the engineer with an understanding of how coating systems are specified, procured, and tested prior to being applied on a large scale to USACE structures. Generally, coating materials can be specified by product name and manufacturer; Federal, military, and other coating formulations; product name or "approved equal"; qualified products list (QPL); and performance. All have inherent merits and limitations; exposure to each will give the engineer a basis for preparing coating specifications. Procurement of USACE coating materials for in-house application is conducted either through the Rock Island Consolidated Paint Acquisition Contract or by using the Government Services Administration (GSA), under regular procurement or the Multiple Award Schedule. Procurement by contractor is the most common method because most USACE work is contract painting. This chapter provides the engineer with an understanding of each of these methods of procurement. Coatings testing—including sampling procedures, material identification, and coating performance tests—is critical in establishing if the supplied coatings meet the formulation requirement and if they will provide corrosion protection to the structure. This chapter will provide the engineer with an understanding of the various tests that can be performed and what the test data mean in terms of coating performance.

3-2. Types of Coating Material Specifications

Coatings specifications can be produced by product name/manufacturer, standard specifications/formulation, product name or approved equal, QPL, and specification by performance. Each type of specification will be discussed.

a. Specification by product name/manufacturer. The product name of a reputable manufacturer is one way to specify a coating material. Although private industry specifies coating material by product name/manufacturer the USACE currently does not. Specifying a coating material by product name is suitable (and advantageous) when a specific coating material has proven successful. If the material is suited for the service environment, it can be expected to continue to perform well. The manufacturer usually will provide technical advice for the application of the material to ensure that it is applied in the best possible manner. A drawback to specifying by product name/manufacturer is that it eliminates competition, and the USACE may pay a

premium price for the product. Refer to 48 CFR 1-10.002 and ER 1110-2-1200 concerning restrictions on specifying proprietary products.

b. Specification by standard specifications/formulation.

(1) Standard specifications are issued by nationally recognized authorities (Federal, military, American Society for Testing and Materials [ASTM], Steel Structures Painting Council [SSPC], etc.) and can be used in selecting paints for civil works activities. Some specifications are formulation based; others are based on product performance. Coating materials specified by formula require the manufacturer to follow a "recipe" during the manufacturing of a coating for a customer. In specification by formula, a coating manufacturer competitively bids on supplying the customer with the product(s) formulated as directed in the specification. No additional expertise is required, and the manufacturer has no responsibility but to supply the product(s) as dictated by the formula specification. For example, SSPC has developed many formula specification materials that have been used since 1955. These formulas were developed because many outstanding coatings that were being studied did not meet available specifications or had specifications for limited distribution. Therefore, the SSPC paint specifications were issued to make it possible for anyone to specify these materials by formulation. SSPC formula-specification paints are widely referenced and accepted throughout the industry. With the exception of those containing lead (to be withdrawn in 1993/1994), SSPC formula coating materials are readily available from several major U.S. manufacturers. Each SSPC Painting System Specification combines all of the requirements necessary for a complete paint job in a single formula. These specifications include all of the components for surface preparation, paint application, paint thickness measurements, primer, midcoat, topcoat, safety, and inspection. There are two methods of using the SSPC Painting System Specifications: specifying the use of an SSPC Painting System Specification by number—recommended for most situations—or using painting system guides to prepare modified systems for special situations. The USACE uses a similar system to specify special formulation vinyl paints commonly used on inland hydraulic structures.

(2) There are limitations to formula specifications. The specified composition may represent a compromise because it may have been developed through laboratory testing only; actual field exposure testing may never have been done. Also, state-of-the-art technology usually is not maintained. For example, the last revision to the SSPC systems was made in 1991. Since then, zinc-filled moisture-cured urethanes and other innovative coatings types have been developed but are not included in the listing.

(3) Much confusion can result from the use of standard specifications for paints and ingredients if the project specification writer does not keep thoroughly up to date and well informed. When a standard specification covers several types or grades of material, the project specification writer may have failed to designate the type and grade of material to be used; thus the contractor, who will be guided by cost considerations rather than applicability, will make the selection. Users of Federal and other standard specifications should consider the comments (Paragraph 9.0, "Notes," in the SSPC Painting System Specification) at the end of such specifications. These comments frequently provide valuable information about intended uses of various classes and grades. Standard specifications can lead to minimum quality manufacturing and materials. A formula coating must be manufactured with tight quality control and tested by the purchaser. When these steps are followed, formula specifications can be a good method of specifying coatings.

c. Specification by product name or "approved equal." Specification by product name may not be desirable because it eliminates competition. The product name or approved equal specification is intended for competitive bidding and often requires the manufacturer to perform tests to prove that the listed materials are equal in performance. Although this type of specification encourages competition, it seldom, if ever, is workable for paint products. "Similar and/or equal" cannot be satisfactorily proven within the short time usually available for compliance testing of the products. "Equal" means equal performance on the contemplated surfaces and under the completed exposure conditions. This type of comparison can be determined only by practical, long-range exposure testing of the product in question alongside the standard of comparison. The "or equal" clause sometimes is avoided by writing a highly restrictive specification around the preferred proprietary product without naming it. This procedure is seen as a ruse by other manufacturers and is more likely to create animosity than if the preferred product is simply specified by name.

d. Specification by QPL. Coatings specification classified by a QPL combines the advantages of coating materials/systems that have been evaluated and approved for use in a given service environment and competitive bidding. A QPL is developed by an owner (i.e., USACE) and implemented by inviting manufacturers to participate in a coatings evaluation program funded by the USACE; or the manufacturer may be encouraged to fund the testing for placement on the QPL. Minimum performance levels are established, and a determination is made about whether or not the manufacturer's product/system is qualified for use. The use of a specification that includes the establishment of a QPL is workable, but it involves considerable time and effort. Under this system, a paint product would be tested

for suitability on practical surfaces for a significant period of time. Those products accepted would be placed on the QPL with the stipulation that the manufacturer furnish exactly the same material as was originally accepted. Failure to do so would result in removal from the list.

e. Specification by performance. A performance specification does not designate the material by formula, but it specifies the required performance of a material. Because all coating jobs are different—with different application and service variables—only comparative testing of coatings under actual field operating conditions will provide an accurate determination about which materials best meet the requirements (e.g., test patches). When performance specifications are based on laboratory test results, they are limited to a few, short-term tests that may not accurately depict the field performance. But the cost and time involved in applying field test patches may dictate the use of laboratory testing. The alleged principal merit of a performance-type specification is that it takes advantage of the manufacturer's knowledge and experience. However, there is no real advantage unless the manufacturer actually is highly experienced in formulating paint for the particular contemplated use and if this experience is actually put to work for the benefit of the consumer. A major difficulty with a performance-type specification is that the acceptance tests, which purport to show that a paint is satisfactory for a practical use, must be finished within a short period of time and may not be dependable in predicting actual performance. For example, passing a 500-hour salt spray test may be a requirement—even though the contemplated exposure does not involve exposure to salt—or passing a flexibility test after 7 days final drying time, whereas a more meaningful test would involve determination of flexibility after years of exposure. These short-term acceptance tests encourage the manufacturer to formulate the product merely to pass the tests rather than to provide long-range, practical performance.

3-3. Coating Material Procurement

Coating materials can be procured by the contractor, the Rock Island Consolidated Paint Acquisition Contract, or the GSA. The advantages and limitations of each source of supply will be discussed.

a. Procurement by contractor. Most painting by the USACE is done by contract, and it is the contractor's responsibility to procure paint that meets the specification. Neither the Rock Island Contract nor GSA normally is made available to the contractor. These sources of supply are for USACE procurement and are used mostly for in-house applications. The USACE may use these sources of procurement to supply the paint to a contractor, but this is

seldom done because the USACE would be responsible for storage, short or excess supply, timely delivery, and hazardous waste.

b. Procurement by Rock Island Consolidated Paint Acquisition Contract. Coating materials can be procured by USACE personnel through the Rock Island District (CENCR). Engineer Regulation ER 700-1-1 identifies CENCR as the Mission Supply Support Activity for special formulation paints outlined in Guide Specification CWGS-09940. Annually, CENCR issues an invitation for bid on a two-part contract. The first part is a fixed quantity contract. Known quantities of various types of paint are clearly outlined, and an agreement to purchase those quantities is included. The second portion of the contract is known as the open-end schedule. This open-end schedule formerly included more paint than the fixed quantity portion; however, in recent years the quantity has been reduced to an amount less than that of the fixed quantity. The open-end schedule is only an agreement by the successful bidder to furnish the materials specified in quantities up to the amounts given by the contract. The Government is not required to purchase any of the quantity on the open-end schedule. To determine the types and amount of paint to be included in the fixed quantity portion of the contract, field offices are surveyed and asked to order the amount of paint they will need for the coming year. Quantities of each type of paint ordered are totaled, assembled into an invitation for bids, and offered to paint manufacturers. The open-end portion is provided for those field offices who were, for one reason or another, unable to determine their needs and for those who underestimated the quantities they would require. On occasion, the total quantity of one or more of the items on the open-end schedule will be purchased. When this occurs, the obligation of the supplier to furnish paint at the contract price ends. However, the supplier usually will continue to furnish the paint at the contract price rather than compete with other paint manufacturers. When the supplies are exhausted or contracts are terminated, procurement of special formulation paints is still the responsibility of the CENCR. Only the special formulation paints, such as all the vinyls and the epoxy zinc primer, are procured through this contract. Prior to 1993, the contract also furnished a number of special formulation phenolic paints. The procurement of these paints was discontinued because of low usage and the fact that one of the phenolics contained lead. The contract cannot furnish Federal or military specification paints or proprietary products. Districts must procure these paints through GSA or other standard procurement practices.

c. GSA—Federal Supply Schedules. The GSA provides a simplified procedure for obtaining commonly used

materials purchased at volume prices through their Federal Supply Schedule (FSS). For many years, the FSS has provided both large and small quantities of paints that meet Government paint specifications. Under this schedule, GSA purchases, stores, and distributes paints, as well as other commodities, for authorized users. The FSS was used by Corps activities mostly for supplying paint for in-house labor. Although it could have been used to provide contractors access to paint, difficulties including storage for early deliveries, claims for late deliveries, and disposal costs for excess materials diminished its use. In recent years, the GSA has expanded the FSS with a "Multiple Award Schedule" (MAS) for some high volume paints.

d. GSA—MAS.

(1) General. The MAS differs from the FSS in that the paints are not purchased according to Government specifications, and GSA does not purchase, store, or distribute the paints. Under the MAS, GSA issues contracts with suppliers for comparable coating materials. GSA accepts the bids and places the names of the multiple suppliers on a list for each generic category of paint. Government agencies may purchase paint directly from the manufacturers at the GSA-negotiated price. At this time, the MAS includes both interior and exterior architectural primers and finish coats. Three levels of gloss are available for each type of finish coat.

(2) Using the MAS. In response to Congressional insistence, the Secretary of Defense is urging the use of commercial materials rather than Government-specification materials. If it is in the Government's interest, contracting officers may authorize contractors to use products from the MAS in performing Government cost-reimbursement contracts and other types of negotiated contracts. Procurement procedures were eased in 1991 so that the limit above which the nonuse of the lowest price item must be justified was raised to \$2,500 or 10 percent of the small purchase threshold (48 CFR 1-13.106). This allows the selection of products from the MAS for many projects without justification for not ordering the lowest cost item. For orders above the \$2,500 limit, justifications can be based on delivery time, special requirements, comparability with existing systems, or special features of the product that are required for effective program performance.

3-4. Paint Testing

Testing of protective coatings (paints) generally falls into three categories: testing of the raw materials, testing of the finished product (material characterization), and performance testing using accelerated weathering and other simulation-type methods of evaluation. The purpose of paint testing is

twofold: to help ensure that the minimum requirements for ingredients and material characterization (e.g., generic type, volume solids, percent zinc in dry paint) are met by the coating manufacturer on a batch basis, and to help ensure that the formulated product will provide satisfactory performance in the environment. The USACE does a fair amount of performance testing, both accelerated (laboratory) testing and field testing. To conduct a credible evaluation and generate meaningful data, comparison of the new product is made with that of a product with a known performance. The products being compared truly must be compared on an equal basis, including equal attention to meeting the recommended surface preparation, application requirements for both the new and the control product, and selecting identical exposure locations in the field. The results of the performance testing are determined in real-time. In some instances this has resulted in products being changed or discontinued and companies going out of business before the test was concluded.

a. Sampling methods and techniques. To a greater degree than many other engineering materials, paints must be sampled and tested to ensure reasonable compliance with the specifications. Plant inspection can ensure that the approved raw materials are entering into the manufacture of the finished products and the correct proportions are being used in the batching. Even a small paint plant carries hundreds of raw materials in stock and makes dozens of finished items by batch. Therefore, specification requirements are greater than for many other construction materials. Sampling and testing are vital to ensure receipt of specified materials. Acceptance of paint manufacturer certificates of compliance and manufacturer's performance test reports is not an advisable practice for paint products. Certificates of compliance from the raw material suppliers typically provide sufficient evidence of the quality of the raw materials. However, this usually is not the concern. Formulating of the raw materials into a finished product and any performance testing conducted by the manufacturer may be suspect. Coating materials may be improperly formulated or may be formulated using less expensive raw materials than those specified. Performance testing conducted by the manufacturer may be biased. For example, the immersion resistance of a coating material may be stated as "excellent" but the test's unstated duration was only 30 days.

(1) Sampling of ingredient materials. In general, examination of only the finished product cannot determine positively that the specified ingredients for particular epoxy coal tar and vinyl paint formulations [shown in detail in the Special Paint Formulations Section of CWGS-09940] were actually used. Immediately on being awarded the contract, the paint manufacturer should be required to submit samples of all raw materials proposed to be incorporated into the

finished products. In addition to samples of the raw materials, the manufacturer should submit a list indicating the trade name and/or code number by which the producer identifies the raw material. These identification provisions often can save considerable analytical work because manufacturers of raw materials frequently indicate in their literature which standard specifications their products comply with. The raw materials should be tested in the laboratory to the extent considered necessary, and a copy of the notice of approval and the raw materials list should be furnished to the plant inspector. Laboratory test results must be submitted in a timely manner so the manufacturer may proceed with making the finished product.

(2) Plant inspection. Actual plant inspection may be advisable in the procurement of large quantities of paint, particularly of the special formulation vinyl-type paints. If adequately carried out, this phase of inspection permits laboratory testing to be minimized. The degree of inspection provided may vary, depending on past experiences with the manufacturer, the nature of the finished products, quantities involved, and other factors. Also, plant inspection is of no value when the paint is specified purely on a performance basis and there are no detailed formulation requirements. A suggested sequence of operations for the inspection of large-quantity items of a paint procurement contract follows.

(a) Sampling of finished product. Samples of finished products should be laboratory tested for color, fineness of grind, consistency, pigment content, volume solids, and similar, easily conducted tests described in subsequent sections of this chapter. If there is doubt about the quality of plant inspection or any question about the accuracy of control and the thoroughness of the manufacturing operations, the samples should be given as complete a chemical and physical analysis as is practicable. If there is concern that the factory sample is truly representative of the product delivered to the field site, a field sample may be obtained and tested.

(b) Container marking. Filled containers should be suitably marked by the plant inspector to ensure that approved materials are shipped. If the finished product is held in storage tanks pending approval by the laboratory, the inspector should seal the storage containers or take other measures to ensure that the material as packaged is identical to that which was sampled and approved.

(c) Batch sampling procedures. Paints are made in batches; thus, a sample from each batch must be taken if sampling is to be representative of a total quantity. Duplicate samples of each batch should be taken if it is deemed necessary to retain an unopened reserve sample in the event of disputes. It appears elementary that the paint

being sampled be thoroughly mixed, yet this is frequently a source of error. Failure to identify samples properly with respect to applicable specification, gallons represented, batch number, and manufacturing date is common; and failure to properly seal the can against spillage during shipment also is frequent.

b. Testing procedures. The large variety of tests for finished paint products generally fall into two categories: material characterization tests and performance tests. Most of these are standard tests described in ASTM Volume 06.01, "Paint—Tests for Formulated Products and Applied Coatings." Federal Test Method Standard (FTMS) 141C, "Paint, Varnish, Lacquer, and Related Materials; Methods for Sampling and Testing" describes additional coating tests. Some of the more common of these material characterization and performance tests are discussed here.

(1) Coating material characterization tests. A series of material characterization tests can be conducted to "fingerprint" finished coatings. The results of the tests can be kept on file and used, if necessary, for comparison with samples from future production batches. This practice provides a method to verify that the material being supplied is similar in formulation to the material that was qualified for use. The results also can be used for comparison with certifications supplied with each batch. If application or performance problems are encountered with subsequent batches, they can be analyzed and the results compared with the original, qualified batch to detect any deviations in composition.

(2) Infrared spectroscopic analysis. Infrared spectroscopic analysis is a common analytical tool in the coatings industry. A conventional infrared spectrometer consists of a source of infrared radiation, a dispersing element to selectively monitor any frequency of radiation, and a detector. The output is termed an infrared spectrum and serves as a "fingerprint" of the resinous vehicle. Typically, an infrared spectrum of the cured coating is obtained. With multicomponent coatings, the components typically are mixed in the proper portions and cured prior to analysis. Scrapings can be taken of the cured sample, and a spectrum can be run using the potassium bromide pellet technique. This involves grinding the scrapings in a mortar and pestle with potassium bromide and fusing the mixture into pellets under high pressure. Spectra of individual components also can be obtained, but a different technique may be required to account for the liquid nature of these samples. Usually, this is a cast film technique in which a small amount of each liquid sample is cast or drawn down as a thin film on a potassium bromide plate and dried to remove solvent. To the trained analyst, an infrared spectrum provides useful information about the composition of the sample. Alkyls,

for example, give dramatically different spectra than urethanes or epoxies. Infrared spectroscopy generally cannot detect minor (<5 percent) differences in formulation. Most additives (flow and wetting agents and others) used in coatings are below this level and do not complicate the spectrum to the point of making a generic identification difficult. A possible exception is the use of certain plasticizers, which sometimes are present in sufficient amounts to complicate the spectrum. An analyst familiar with paint formulation can recognize this complication for what it is, and no difficulties arise. But in some instances additional analytical techniques, such as size exclusion or gel permeation chromatography, can be used to separate and isolate the additives and allow unambiguous identification of the vehicle.

(3) Volume solids. Testing for solids by volume, or volume solids, is performed by Method ASTM D2697. Whereas the weight solids test determines the percentage by weight of nonvolatile matter in a coating, the volume solids test determines the percentage by volume of nonvolatile materials. This test is somewhat more tedious than the weight solids test and involves the coating and weighing of metal coupons both in air and when suspended in water. Though somewhat more difficult to obtain, the volume solids test generally is more representative of how a paint will perform in terms of coverage. Coatings containing a volume solids content lower than specified will result in additional material cost because of an increase in the amount of coating material required to cover a given area.

(4) Nonvolatile content (weight solids). This test usually is conducted according to ASTM D2369 and is a determination of the percentage by weight of solids in the coating. The technique is simple and straightforward; it involves weighing small samples of wet paint both before and after heating in an oven maintained at 110 °C (230 °F). Weight solids can affect coating cost and performance, and they directly affect the application properties. Sagging, orange peel, and insufficient dry coating thickness may result if the weight solids is insufficient. Also, the weight solids is directly related to the VOC of the coating. The VOC level is determined by multiplying the weight volatile by the density (weight per gallon) of the coating.

(5) Density/weight per gallon. Commonly referred to as weight-gallon, this test usually is performed according to ASTM D1475. The weight of wet paint needed to just fill a special weight gallon cup is determined; and the density of the paint in pounds per gallon can be determined from this amount of paint. The density of a coating material also is related to the VOC of the coating.

(6) Viscosity. There are many ways to measure the

viscosity of a coating. Efflux cups, such as the Ford and Zahn, measure how long it takes for a certain amount of coating to pass through an orifice of a specified dimension. These cups are common in both the field and the laboratory. The Krebs-Stormer and Brookfield Viscometers consist of a motor turning a paddle or spindle, and they measure the resistance imparted by the paint. These instruments are common in the laboratory. Viscosity and volume solids are interrelated and impact the performance and ease of application, thinning, and flow-out of the coating material. For example, if a coating material is too viscous (high viscosity), orange peel, gun spattering, and a general lack of ability for the coating to knit together when applied will occur. Solvent entrapment also may occur. Conversely, if a coating is too thin (low viscosity), runs, sags, drips, and other application-related defects may occur.

(7) Drying time. As with viscosity measurements, there are a number of ways to determine the drying time of a coating. ASTM D1640 outlines eight methods for determining drying time: set-to-touch, dust free, tack free, dry-to-touch, dry hard, dry through (handle), dry-to-recoat, and print free. Of the eight methods, dry-to-touch and dry hard are the two most commonly referenced in specifications. This information is useful in determining whether the coating is formulated to dry or cure as stated by the manufacturer. Coatings that exceed the dry time either do not contain sufficient driers or do not chemically react properly after being catalyzed.

c. Coating system performance tests. Coating system performance tests must be carefully selected and must be based on the service environment or intended use. For example, a corrosion resistance test performed on a coating system intended for use in an office building would be both wasteful and unenlightening. This is an obvious example of mis-selecting a performance test. The selection of which laboratory test or test series will accurately depict field conditions is not always clear-cut. For example, a USACE dam frequently is subjected to the synergistic effects of immersion, abrasion, impact, and other conditions. The effect of a dislodged tree impacting and sliding along a dam gate is difficult to duplicate in the laboratory. Although it is important to select performance tests that are representative of field conditions, laboratory testing rarely, if ever, duplicates actual field conditions, and relative comparisons must be made against the performance of known control systems to obtain meaningful data. A listing of common performance tests and a brief description of each follows.

(1) Adhesion. Perhaps the most fundamental requirement of a coating is that it adhere to the substrate and to previous coats. As important and fundamental as this

performance property is, the method used to assess it frequently relies on the common penknife. Although cutting, gouging, and chipping may give valuable adhesion information, the knife test is somewhat subjective. However, there are two other convenient, widely used methods that provide somewhat more quantitative data: tape adhesion testing and tensile adhesion testing. Although each test evaluates the adhesion characteristics of coatings, data have shown that results from tape adhesion testing may vary dramatically from results obtained by tensile adhesion testing, perhaps because the tape test evaluates shear adhesion strength rather than tensile adhesion.

(a) Tape adhesion. The tape adhesion test method is described in ASTM D3359, Method A (X-cut tape test) or Method B (crosscut tape test). The procedure for creating the crosscut involves making a series of closely spaced parallel knife cuts through the coating and making a second series perpendicular to the first; a special pressure-sensitive adhesive tape is applied to the grid pattern. The tape is rapidly removed, and the crosscut or grid area is inspected for coating removal. A standard included with the method rates the adhesion from a maximum rating of 5 to a minimum rating of 0. Tape adhesion is used to evaluate a coating's ability to adhere to underlying coats and to the substrate. Tape adhesion frequently is used to qualify the existing coating for topcoatability (the ability of underlying coats to withstand the stresses of topcoating). However, adhesion testing is not an indicator of product performance. From a corrosion protection viewpoint, a coating with an adhesion value of 2 or 3 probably will protect as well as a coating with an adhesion value of 4 or 5.

(b) Tensile adhesion. Tensile adhesion can be measured with instruments described in ASTM D4541. Briefly, pull-stubs are bonded to the coating surface with adhesive and allowed to cure thoroughly, sometimes overnight. The instrument then measures the force required (in pounds per square inch) to disbond the coating by placing increasing tensile force on the pull-stub. Tensile adhesion also will reveal the weakest link in the coating system whether between two coats, within a coat, or between the substrate and first coat. In some situations, the coating adhesion exceeds the strength of the adhesive used to adhere the pull-stub. As with tape adhesion, tensile adhesion is not a true indicator of performance or corrosion protection. A coating system with a value of 350 psi probably will protect as long as a system with a value of 700 psi. In fact, a range of results spreading 100 to 200 psi may be found on the same substrate/coating system, and research has shown that results among tensile adhesion test instruments can vary even more. Therefore, tensile adhesion testing should be performed using one type of tester, several test stubs should be pulled, and a range of test results should be provided.

(c) Interpreting adhesion results. ASTM standards are useful in describing test equipment and procedures. However, ASTM rarely provides information about the meaning of the test results. Most individuals would consider a tape adhesion rating of 5 to be good and 0 to be bad; however, there is little agreement on the intermediate results (ratings of 4, 3, 2, or 1). Furthermore, there usually is less agreement on the results for tensile adhesion testing because of the lack of reproducibility and differences in values obtained from different adhesion testing instruments. But adhesion testing has a relative value for acquiring comparative adhesion test data despite the limitations.

(2) Hardness. Several methods for evaluating hardness exist and are thoroughly described in the Gardner-Sward Paint Testing Manual. Pencil hardness is probably the most widely referenced method in most manufacturer's product data sheets. The true meaning of the hardness result is not always evident. The tests can be used to determine which coatings are harder or softer than other coatings, but the required degree of hardness or softness is not always obvious. Indeed, for some applications such as flexible elastomeric coatings, hardness may actually be considered detrimental.

(a) Pencil hardness is described in ASTM D3363 and the National Coil Coatings Association Bulletin II-12. The hardness of a lead pencil required to rupture a coating is recorded and termed the pencil hardness. Because the technician uses hand pressure on the pencil, the result of the test is somewhat subjective and can vary from technician to technician.

(b) For thicker coatings and plastics, Barcol Hardness (ASTM D2583) and Shore Durometer Hardness (ASTM D2240) can be used. The durometer is a hand-held device with a sharp needle on one face that is firmly pressed against the coating. The degree of penetration of the needle is reflected by the pointer on the instrument scale. The Barcol impresser operates on a similar principle. The tests can be conducted rapidly and easily, and both tests provide numerical results.

(3) Flexibility. Test methods for measuring flexibility include ASTM D522 and Federal Test Method 6221. These methods involve the bending of a coated substrate over a mandrel and determining the amount of bending that can take place before the coating cracks. With ASTM D522, a conical mandrel can be used as well as cylindrical mandrels, and a calculation of the coating material's percent elongation can be determined. The inherent flexibility of a coating is related to its ability to protect edges, weld seams, and steel imperfections; and it is related to the impact resistance of a coating. For example, after a coating with limited flexibility

is cured, it may crack and disbond over any uneven surfaces or on impact. To a lesser degree, a coating's flexibility will aid in withstanding the stresses of steel expansion and contraction during freeze/thaw or other temperature fluctuations.

(4) Impact resistance. In addition to flexing, certain applications require that a coating be resistant to impact damage. Impact resistance and flexibility are related coating properties. "Deformation (impact)" is commonly used and involves dropping a known weight from various heights until the coating fractures or disbonds. The result is reported in inch per pound, and thus has the advantage of a numerical rating, which can easily be compared from one coating to another. An example of this application is the coating on USACE dam gates, which frequently are subjected to impact damage from floating debris.

(5) Abrasion resistance. If a coating is expected to be exposed to continued sources of abrasion damage, a measure of its abrasion resistance is desirable. A convenient and rapid method of measuring abrasion resistance is the Taber Abrasion method, described in ASTM D4060. Although ASTM reports that this method exhibits poor interlaboratory reproducibility, it is one of the most widely known and specified methods. A coated test plate is mounted on a turntable that rotates under a pair of weighted abrading wheels, and the weight of coating loss per thousand revolutions is measured. Although it may be difficult to select an actual abrasion resistance rating, the test is useful for comparing the abrasion resistance of one coating with that of another. Unfortunately, poor correlation has been found between this test and an environment in which floating debris gives more impact and cutting damage than abrasion damage.

(6) Accelerated weathering. The performance tests discussed here all have one thing in common: they are typically used to measure the initial properties of a coating. However, the real-world environment is considerably different from the laboratory environment. Although a perfect simulation of the real world may never be achieved, several tests that attempt to provide information about coating performance over the long term have been developed. This is known as accelerated weathering testing. A coating's ability to withstand the outdoor environment is called its weather resistance, and a variety of devices have been developed to measure it. The elements most commonly associated with outdoor weathering are light, heat, moisture, and oxygen. Therefore, although different in their actual method of operation, the various accelerated weathering instruments all rely on some combination of these elements in varying levels of intensity to degrade coatings. Moisture may be introduced by spray,

condensation, or immersion; the damaging UV component of sunlight may be introduced by either arcs or fluorescent tubes. Regardless of the apparatus used, this test, as is true of so many other accelerated tests, primarily is useful in generating comparative results; and efforts to relate the number of hours of artificial weathering to a period of natural weathering are difficult at best, and probably impossible. Common tests for weathering are: ASTM G23, ASTM G26, and ASTM G53. Although the duration of testing cannot be directly correlated to natural weathering, it is common to see test results based on an exposure period of 1,000 hours. The properties measured usually consist of loss of gloss, chalking, crazing, blistering, or other visual defects. Physical properties (adhesion, hardness, flexibility, etc.) also can be measured both before and after accelerated weathering.

(7) Corrosion resistance. Another common requirement of protective coatings and linings is that they have good corrosion resistance. The ability of a coating to provide barrier protection between the steel substrate and the environment is an inherent corrosion protection factor. Coatings systems subjected to immersion, splash, salt water, chemical solutions, and other corrosion-causing elements should be evaluated for their relative resistance. The coating systems being evaluated may be intentionally damaged (scribed) to simulate abrasion or impact damage and the coating's ability to resist undercutting corrosion examined. As simple as this requirement sounds, the ability to accurately measure corrosion resistance in the laboratory is a subject of controversy.

(a) Salt fog. The most commonly performed corrosion resistance test is the salt spray or salt fog test described in ASTM B117. Coated panels are placed in a closed cabinet and exposed to a warm mist of atomized, neutral 5 percent sodium chloride solution. The duration of the test varies considerably, depending on the intended use of the coating. Aerosol paints designed for consumer use (e.g., lawn furniture) may last only a few days in a salt fog cabinet before severe blistering and corrosion occur. Conversely, inorganic zinc-rich primers designed for use on structural steel can last thousands of hours before rusting is evident. Salt spray test data should be regarded as comparative test data only; it usually is impossible to extrapolate from salt spray results to obtain an expected service life under field conditions. There is some controversy about whether salt spray testing even remotely resembles the conditions seen in actual service, and some studies show that certain coatings that perform poorly in salt spray perform well in the field, and vice versa.

(b) Prohesion. The Mebon Prohesion Cabinet, widely used in Europe, is an accelerated corrosion device that some studies indicate provides more reliable results than salt

spray. The device is not recognized by ASTM at this time (1995). The mist atomized into the cabinet is not the 5 percent sodium chloride solution used in ASTM B117, but a dilute solution of ammonium sulfate and sodium chloride termed "Harrison Solution." The solution is atomized at room temperature rather than the elevated temperature of the salt spray cabinet; it is purged with dry air to produce a cyclic condition of wetting and drying. The results of this testing should be used as comparative data only.

(c) Humidity. Coatings can be exposed to moisture without being exposed to salt. Methods are described by ASTM D2247 and D4585. These methods expose coated panels to either warm, 100 percent relative humidity or warm condensation. The most common failure mechanism is blistering. A common test duration is 1000 hours, which provides comparative test data but does not allow an extrapolation to length of field service.

(8) Chemical resistance. A common use of coating materials is protection from chemicals, either in a generalized industrial environment or, with linings, in specific reaction or storage vessels. In the former instance, the selection of an appropriate and meaningful test can be difficult because attempts to simulate an industrial environment may be infinitely variable. However, testing that closely duplicates the actual field service conditions frequently can be performed.

(a) If, for instance, that the intended use of a coating is to line a carbon steel vessel to be used for the storage of dilute sulfuric acid, coated test coupons can be immersed in the same acid at the same concentration. The test coupons can be tested at either ambient temperature or at an elevated temperature (if representative of field conditions) to achieve accelerated results. A convenient way of evaluating coatings is described by ASTM D1308. Coatings may be tested for simple spot resistance by applying the chemical or substance to a coated panel and covering it with a watch glass, or by immersing coated panels in beakers containing test solutions. Elevated temperatures also may be used.

(b) A more aggressive and versatile method of evaluating chemical resistance involves the use of a one-sided testing apparatus described by both NACE TM-01-74 and ASTM C868. The test cells consist of a glass cylinder with connections for condensers, heaters, and thermometers. The coated test specimens are mounted in a way to constitute the ends of the cylinder, and are sealed to the cylinders through the use of gasketing and bolt/nut fixtures. The cell is filled approximately one half to two thirds full with the desired test solution, and a heater is used to achieve the desired temperature. A water-cooled condenser prevents evaporation of the solution. A wide variety of chemicals can be tested at various temperatures, plus the design of the

apparatus permits simultaneous testing of the coating in both the immersion phase (lower one half to two thirds) and the vapor phase (upper one half to one third). The cells can be disassembled, and the coating can be evaluated periodically for blistering, corrosion, cracking, discoloration, or other visual defects in both the liquid and the vapor phases.

(9) Field testing. An important criterion for including a particular coating in a specification is the availability of historical field data in similar or identical facilities or environments. In addition to historical data, if time permits, test panels prepared with the candidate coating systems can be prepared and installed at the site. This may involve placing coated panels on test racks exposed to the general atmospheric environment or actually mounting panels in an immersion or splash zone. If such testing is undertaken, enough coated test panels should be used so they can be removed at specific time intervals to ascertain the rate of coating system degradation. An even better method than placement of coated test panels is to apply test patches of candidate coating materials to the actual structure. Careful (and thorough) documentation should be maintained during the application of test patches (surface preparation, application conditions, etc.) because this information will prove invaluable during full-scale application. Field testing utilizing coated test panels or field test patches is the optimum "litmus" for determining the suitability of a coating system for a given service environment. Much of the manufacturer's published data are based on accelerated weathering testing, which does not accurately predict the performance of the coating system.

d. Interpretation and accuracy of test results. The most common problem that arises in paint testing and the interpretation of results concerns deficiencies small enough to raise a question about whether the material should be rejected or accepted. This problem is bound to arise in formulation-type specifications, regardless of whether the specified percentages of ingredient materials are on an absolute, zero-range basis or a minimum-maximum range is provided. Some persons believe that, if the specification provides a range of percentages for the various ingredients in a paint, the manufacturer is somehow obligated to more than meet the barest (least costly) requirements. Logically, however, this viewpoint is not supported; a paint that contains the required minimum percentages of the more expensive ingredients and does not go above the permissible maximum for the less expensive ingredients meets the specification just as completely as a paint in which the manufacturer has been more liberal.

(1) Variance thresholds. The first question in deciding whether a minor deviation from the specification warrants

rejection of a batch of paint is the accuracy of the test result. Even when conducted in the most competent and experienced laboratories, a prescribed and analytical test method is capable of only a limited degree of precision. Another unavoidable source of possible error may be the characteristics of an individual laboratory. A typical example of a peculiarity may be that the laboratory consistently obtains low results in analyzing an alkyd paint vehicle for phthalic anhydride content. A deviation revealed by testing that is smaller than the bias error of a laboratory obviously should not be used as the basis for rejecting a batch of paint. In addition, rejecting a paint because of an apparent deviation—when the result is within the inherent limits of the test method—raises a serious question. Some specifications attempt to bypass the question of rejection because of small deviations (which are within the limits of experimental error) by stating that, on analysis, the paint shall show the specified amount of an ingredients. This raises the interesting question for the manufacturer about how to adjust the indicated ingredient proportions so they test within the specification limits—assuming the manufacturer recognizes the subtleties of the wording in the specification.

(2) Clarification of variances. If a paint is still deficient after a justifiable allowance is made for the degree of precision inherent in a prescribed test method, a decision must be made about whether the deficiency is serious enough to warrant rejection. This decision may vary in specific situations, and no attempt will be made here to suggest guidelines. Among the factors that may influence a decision are: the magnitude of the deficiency, the estimated effect of the deficiency, if there is more than one deficiency, if deficiencies are balanced by positive features in which the manufacturer has more than met the specification, fairness to other potential suppliers, etc. Nothing significant to the paint's performance should be sacrificed; however, stiff, unyielding adherence to the specification ultimately may not serve the best interests of the Government. Four alternatives related to the interpretation of test results include:

- The test result complies with the specification's stated test data, and the paint may be recommended for use.
- The test result deviates from the specification's stated test data but is within laboratory experimental error; and the paint may be recommended for use.
- The test result deviates from the specification's stated test data and is outside of experimental error; however, the deviation is believed to be unrelated to

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the performance characteristics of the coating material. Therefore, the material may be recommended for use.

- The test result deviates from the specification's stated test data and is outside of experimental error; and the deviation is believed to affect the performance life of a coating. Therefore, the coating may not be

recommended for use.

(3) Testing laboratories are not permitted to approve or disapprove a paint; they can only recommend acceptance or rejection to the contracting officer. In some instances, the laboratory will check with the field office about the specific use of a paint before making a recommendation on a paint that fails specific tests.

Chapter 4 Coating Types and Characteristics

4-1. Introduction

a. All coatings—whether used for corrosion protection, to provide good aesthetics or a pleasing appearance, or for any other purpose—will contain a film-forming material. This material may be organic or inorganic and, after application, may form a hard, impervious film, a soft porous film, or combinations in between. Furthermore, the film-forming material may be clear (unpigmented) or filled with a variety of different pigments, depending on its function. When the film-forming material (resin) contains pigments, it is called a binder. The binder will hold the pigment particles together and to the substrate over which it has been applied. When the binder (resin plus pigment) is dissolved in a solvent to make it liquid, the combination (solvent, binder, and pigment) is considered to be a vehicle. The term vehicle comes from the ability to transport and apply the liquid to the surface being coated. Once on the surface, the solvent evaporates and the vehicle becomes a pigment-binder system. Application properties of the paint usually are characterized by the vehicle in a liquid condition. The viscosity, rate of solvent evaporation, and consistency of the wet coating are most important during application. After application, the pigments determine the corrosion-inhibitive properties and, generally, the color and some flow control properties of the applied coating. The binder determines the weatherability of the coating, its environmental resistance, and the coating's ability to function in a given environment. The required surface preparation, and often the application equipment and techniques, are determined by the binder.

b. The principal mechanisms by which binders form films are reaction with oxygen from the air (oxidation), evaporation of the solvent from the vehicle (solvent evaporation), or chemical crosslinking (polymerization). The coating film attained by these mechanisms can be either thermoplastic or thermosetting. Thermoplastic materials deform and soften on exposure to heat. Thermoset materials do not deform and remain hard upon heat exposure. Each type of coating resin or binder categorized by its film-forming mechanism, different types of pigments, and the various solvent families will be discussed. Drying oils are an integral part of some coating formulations, and they as well as driers that aid in the drying reaction will be covered. Miscellaneous additives that are formulated into many coatings for specific purposes are itemized and discussed. Sections are presented on powder coatings, thermal spray organic and inorganic coatings, and galvanizing tapes and wraps. Problems with VOCs also will be discussed.

4-2. Film-Forming Mechanisms

Coating binders can be subcategorized according to the mechanism described above. However, with both oxidation and most polymerization film-forming mechanisms, solvent evaporation occurs initially, followed by a subsequent chemical reaction consisting of either a reaction with oxygen or chemical crosslinking. Solvent evaporative coatings also are called thermoplastics because, when heated, they become plastic and can soften and deform. Oxidation and chemically crosslinked coatings “set” and harden when cured; they do not soften or deform on heating and, therefore, are called thermosets. After application, most coatings “dry” by solvent evaporation to form a film that feels dry to the touch. However, the dried coating may not be cured, and additional chemical reactions may be required. Oxidation coatings require crosslinking with oxygen from the air, and polymerization coatings require a crosslinking chemical reaction between two or more coreactants to attain their final physical and chemical properties.

a. Oxidation (thermoset). Thermoset coating types dry and ultimately crosslink by reaction with oxygen from the atmosphere. All such coatings in this class contain drying oils that consist mainly of polyunsaturated fatty acids. The drying oil frequently is combined with a resin, usually by cooking or heating to enhance water and chemical resistance. The curing reaction is accelerated by the presence of metallic salts as driers. After application, the coating dries by solvent evaporation. However, to attain maximum chemical and moisture-resistance properties, the oil must react with oxygen from the air to crosslink, cure, and further harden. The auto-oxidation reaction occurs at a relatively fast rate shortly after application of the wet paint; and it continues throughout the life of the coating, although at a much slower rate. For most oil-based coatings, suitable moisture and chemical resistance occur within a few days after application, although maximum resistances may not be obtained until months or years after application. In time (often 20 or 30 years later), the oxidation reaction and continued drying of the oleoresinous binder system leads to cracking, embrittlement, and deterioration of the coating film.

b. Solvent evaporation (thermoplastic). A second film-forming mechanism is solvent evaporation. The solvent within which the resin is dissolved or emulsified may be water or an organic solvent. The liquid resin returns to a solid material when the solvent evaporates. The coating is formed as a result of solvent evaporation and drying, with no attendant crosslinking or polymerization. Solvent-based coating systems that dry solely by solvent evaporation (vinyls and chlorinated rubbers) have their usage severely

restricted because of VOC regulations. These resins must be dissolved in relatively high amounts of noncompliant solvents to be formulated into a corrosion-resistance protective coating. Latex emulsion coatings consist of pigmented synthetic resin particles emulsified in water. Because latex emulsion coatings dry by water evaporation (and perhaps one percent or less of a coalescing organic solvent), coatings formulated in this fashion comply with VOC legislation; and they have rapidly advanced in recent years to become environmentally safe, long-lasting, protective coating systems. Thermoplastic coatings in the context used here are coatings that dry principally, or solely, by water or solvent evaporation; they do not undergo chemical crosslinking. Principal coatings in this class are acrylic lattices, solvent cutbacks, and hot melt bituminous coatings and vinyl coatings (zinc chromate vinyl butyral wash primers, vinyl chloride-vinyl acetate copolymers, and waterborne vinyls).

c. *Chemically crosslinked (thermoset).* Thermoset coatings, by definition, are coatings that are "set," and are nondeformable when exposed to elevated temperatures. Thermoset coatings achieve their characteristic "set" and the ability to resist heat deformation by virtue of a three-dimensional crosslinking. This crosslinking is achieved by coreacting two or more monomers, with at least one monomer having a functionality of three or greater, and the other a functionality of at least two. (The functionality is the number of reaction sites where crosslinking can occur.) This film-forming mechanism involves a chemical reaction combining smaller molecules (mers) to create a larger molecule (polymers). The reactions can consist of the same kind of mer units reacting to form larger molecules (homopolymers) or different mer units reacting to form copolymers, tripolymers, or, generically, polymers. After crosslinking, and depending on the type and extent of crosslinking, the resin system is solvent resistant, ranges from tough and flexible to hard and brittle, and does not significantly deform on the application of heat. In coating formulations, most coreactive coating systems are supplied in multipack systems consisting of two or more containers that must be mixed prior to application. However, some thermoset materials react with moisture from the air (moisture and ketimine curing isocyanates) and can be supplied as a one-package system. After application in all instances, the coating system, when properly applied and cured, forms a single, extremely large molecule by virtue of its polyfunctional crosslinking. When suitably dissolved in a solvent and pigmented, many coreactive materials can be formulated into a protective coating. Some of the more commonly used protective coating systems are based on catalyzed epoxy resins, polyurethane reactions, acrylic/vinyl ester resins, and modifications thereof. Each of these coating systems will be discussed later. Polymerization

reactions are becoming increasingly important in the formulation of modern VOC-compliant coating systems. Small molecule units, that by virtue of their low molecular weight are liquid, can be reacted with other low molecular weight liquid molecules to form a higher molecular weight molecule that will harden to form a solid (nonliquid) protective film. The most successful adaptations to manufacturing low VOC coatings have been two-pack, chemically cured coating systems such as the epoxy, polyurethane, polyester, and vinyl ester systems.

4-3. Binders (Resins)

The binder, sometimes called a resin, and a suitable solvent (to make it liquid) are combined to form the vehicle. Pigment particles then are dispersed and mixed into the liquid resin, and the paint is packaged, usually in a can or pail, for sale. Upon use, the liquid paint is applied—perhaps by brush, roller, or spray—after which the solvent volatilizes, the liquid resin dries or cures, and the pigment particles "bind" together and to the surface being painted. Binders may be natural or synthetic resins and may be organic or inorganic. The binder used in a particular coating system is primarily responsible for the coating's chemical, water, and UV light-resistant properties. However, to optimize protective capabilities, most coatings must be pigmented to provide color and opacity, to reduce shrinkage, and to obtain enhanced moisture and chemical resistance. When properly applied and dried and/or cured, the pigmented binder provides the decorative, protective layer referred to as a paint or coating. The characteristic of the binder and its method of drying and/or curing determines the mechanism of film formation. Many of the natural resins used as binders are derived from exudations from trees or insect secretions. Synthetic binders are generally by-products of chemical refining or manufacturing processes. These resins are man-made and, when refined and modified for coatings use, can be used as film formers for protective and decorative coatings. Because of their improved moisture, chemical, and UV resistant properties compared with the natural resins, synthetic resins have obtained widespread use in a variety of different service environments as corrosion-protective coatings.

a. *Natural resins (oxidative).* Natural resins are derived from tree exudations, fossilized vegetable remains, or insect secretions. Natural resins derived from tree exudation may be named after the region from which they originated; this accounts for some exotic names such as Kauri, Batu, Sandric, and others. Natural resins generally are cooked with drying oils to make varnishes with faster drying rates, higher gloss, and harder films than can be attained from the oil alone. Some were used as a sole binder in so-called spirit varnishes, i.e., the resin was simply dissolved in

volatile solvents. When applied to a surface, the solvent evaporated from the spirit varnish leaving a film of the resin on the substrate. This type of drying mechanism involves no substantial chemical change and is typical of what today is called lacquer. In general, clear films of natural resin, oil varnishes, and spar varnishes have poor exterior durability. Accordingly, these resins are no longer used extensively except for interior use such as for wood furniture finishing.

(1) Rosins. The natural resin, rosin, is obtained from oleoresin, a sap exudation of pine trees. Lighter fractions (i.e., the fastest evaporating, when heated, also usually the lowest molecular weight) of the sap include turpentine, dipentene, and pine oil. Rosins generally have a high acid value and poor resistance to water and alkalies. They also are sensitive to oxygen in the air and are tacky to the touch. Rosins are most commonly used to produce rosin maleic esters, and they are adducted (partially reacted) with maleic anhydride and then esterified with glycerol. These esters sometimes are combined with castor and/or soya oils to reduce yellowing and to increase the hardness and gloss of paints. Coatings manufactured from rosin maleic ester binders are clear and unpigmented and are intended for interior wood surfaces and furniture finishes.

(2) Shellac. Lac is a resinous secretion of a coccid insect from India and Thailand used to make shellac. The dry secretion is collected, crushed, and washed. Afterward, it is melted and dried in sheets that are broken up and exported for use as an alcohol-soluble coating resin. The shellac film is both hard and fairly elastic, and it has a variety of uses including knot sealers and sealers for wood and plaster.

(3) Copals. Natural resins called copals are derived from fossilized or semifossilized vegetable remains. These resins have high carboxyl-functional hydrocarbons of high acid number and, therefore, are reactive. The fossil resins frequently are cooked with vegetable oils to result in a resin with an improved drying time, hardness, gloss, and water or alkali resistance. Because of their flexibility, these resins most commonly are used for coating paper (paper labels).

b. Oil-based alkyds (oxidative).

(1) Alkyd resins are derived as a reaction product of polyhydric alcohols and polybasic acids. Alkyds use a polybasic acid derived from a semidrying or drying oil so the resin formed can undergo auto-oxidation at any temperature. This definition also includes polyester resins, of which alkyds are a specific type. The properties of alkyd coatings predominantly are the result of the properties of the drying oil used in the manufacture of the alkyd resin. Drying time, hardness, color, and moisture sensitivity all

depend on the drying oil, its type, and the degree of unsaturation (available crosslinking sites). Soybean oil has been shown to give good drying rates and good color retention. However, linseed oils generally dry faster but darken on exposure to light. Castor and coconut oils have good color-retentive properties and are used as plasticizing resins because of their nonoxidizing characteristics.

(2) The amount of oil combined with the resin influences the protective capability of the applied alkyd coating. Long oil modifications (greater than 94.6 liters [25 gallons] of oil per 45.36 kilograms [100 pounds] of resin) result in less moisture and chemical resistance and longer drying times. However, long oil alkyds have a greater ability to penetrate and seal a poorly cleaned surface. Short oil alkyds (less than 37.85 liters [10 gallons] of oil per 45.36 kilograms [100 pounds] of resin) are fast-drying coatings that usually require baking to attain full cure (approximately 95 °C (200 °F)) for a few minutes. Short oil coatings have good moisture and chemical resistance but are relatively hard and brittle. Medium oil alkyds (37.85 to 94.6 liters [10 to 25 gallons] of oil per 45.36 kilograms [100 pounds] of resin) are a practical compromise between the long and short oil modifications. They usually dry hard within 24 hours and are the oil length of choice for most new and maintenance alkyd coating systems.

(3) All alkyd coating systems initially dry by solvent evaporation and cure by auto-oxidative crosslinking of the oil constituent. Because of the presence of the drying oil, alkyd coating systems have limited chemical and moisture resistance, cannot be used in highly chemical environments (acid or alkali), and are not resistant to immersion or near immersion condensing conditions. However, their relatively low cost, ease of mixing and application, and excellent ability to penetrate and adhere to relatively poorly prepared, rough, dirty, or chalked surfaces make them the coating system of choice on steel exposed to nonchemical atmospheric service. Alkyd coatings are widely used for structural steel such as the exterior of buildings, handrails, cranes, gantries, etc. Alkyd coating systems should not be used in immersion or in environments in which the coating will be subjected to prolonged wetting, dampness, or condensing humidity. Because drying oils are saponified by alkalies, they should not be applied to alkaline surfaces, including applications over galvanizing (as a result of the alkaline nature of zinc hydroxide, a corrosion product of zinc), concrete, mortar, and most cementitious surfaces (as a result of inherent alkalinity because of the use of lime as a component of cement).

c. Alkyd modification (oxidative). Alkyds are perhaps the most widely used industrial protective coating by virtue of their ease of application, relatively low cost, color

stability, and good weather ability in most atmospheric environments; therefore, it is reasonable to assume that coating formulators would seek to improve properties of the drying oil alkyd by modification with other resin types. Although these modifications will somewhat increase the cost of the coating system, improved properties usually result and make the modification cost effective.

(1) Phenolic modification. Modification with a phenolic resin improves gloss retention, water, and alkali resistance. Phenolic alkyd resins have performed satisfactorily in water immersion, a service in which nonphenolic modified alkyd resins are not suitable.

(2) Vinyl modifications. Alkyd resins with vinyl modification are commonly formulated as universal primers. These primers generally can be topcoated with most generic-type intermediate and topcoats. The alkyd constituent improves adhesion, film build, and solvent and thermal resistance; the vinyl modification enhances recoatability and chemical and moisture resistance. These coatings frequently are used as shop primers or as tie coats between different generic coatings (e.g., over inorganic, zinc-rich primers or between alkyd primers and epoxy topcoats).

(3) Silicone modifications. Silicone modification of alkyd resins is perhaps the most widely promoted modification for corrosion-protective coatings. A silicone intermediate is added to the alkyd resin in quantities up to 30 percent to provide polymers with greatly improved durability, gloss retention, and heat resistance. Moisture resistance is greatly improved by the silicone modification, and this type of paint is used extensively as marine and maintenance paint.

(4) Epoxy modifications. Alkyd resins can be combined with epoxy resins to produce coatings with improved chemical and moisture-resistant properties. Epoxy ester coatings are similar to alkyds, and they are used when improved performance is required. Epoxy esters result from the direct esterification of an epoxy resin and a fatty acid such as a vegetable oil or rosin. The resulting epoxy ester resin is prepared by reacting it with drying oil by heating in the presence of an esterification catalyst. The same drying oils used to prepare alkyds also are used to prepare epoxy esters. Oil length is categorized as long, medium, and short with properties similar to those for alkyds. Epoxy resin oil-based coatings have better adhesion, moisture, and chemical resistance than alkyds, although they are slightly more expensive. These coatings are used as baking and air dry original equipment manufacturers' coatings applied to appliances, machinery, pumps, valves, etc.

(5) Urethane modifications. Alkyd resins are commonly reacted with isocyanates to form a so-called uralkyd or

urethane oil coating. The isocyanate reaction decreases the drying time of the coating and provides enhanced resistance to chemicals, moisture, weathering, and abrasion. Uralkyd coatings are used as marine coatings of wood boat hulls, machinery enamels, and an upgrade to an alkyd coating.

d. Waterborne acrylic emulsion coating. An emulsion is essentially a dispersion of droplets of one liquid in another liquid, in which the first is not normally soluble. Examples of emulsions are milk and mayonnaise; in both of these, fat globules are disbursed in water. For paints, emulsion technology is promising for VOC compliance because water is not a restricted solvent, and only small amounts of solvents—called coalescing solvents—are required in the formulation. The resin is polymerized to a relatively high molecular weight (10,000 or higher) in emulsion paints. The pigment is incorporated in the resin, and the semisolid resin-pigment polymer is emulsified in water. Acrylic polymers are especially popular as an emulsion resin because they provide coatings with unexcelled color retention and have excellent exterior weathering and durability properties. The hardness and flexibility of emulsion polymers vary considerably because of the types and amounts of monomers used in their molecular weights. Methyl methacrylate monomer gives the hardest thermoplastic polymer, and acrylate monomers yield the softest product. Copolymers of acrylic and methacrylic esters are used extensively for exterior acrylic emulsion paints. Vinyl acetate-acrylic copolymers also are popular, particularly for interior use. The acrylic constituent upgrades water and alkali resistance, film flexibility, and durability; and it acts as a permanent plasticizer for the vinyl acetate.

(1) Styrene-acrylic. Styrene-acrylic waterborne systems in which the styrene is copolymerized with lower alkylacrylates have gained in importance. They are characterized by high gloss and good gloss retention. When properly formulated, they dry quickly and develop good film hardness. Styrene-acrylic systems are used primarily as interior house paints or as coatings for relatively mild interior industrial service conditions. These coatings may yellow on exterior exposure and do not have good moisture resistance. They also are used as concrete block fillers.

(2) Latex emulsions. Latex emulsion coating systems have gained in popularity because of their ease of application and cleanup and their good color retention and durability on exterior surfaces. One hundred percent acrylic copolymer formulations have been developed that provide good protection as complete water-based systems (primer, intermediate, and topcoat) on blast-cleaned structural steel. Acrylic latex coating systems also are used extensively for protecting aluminum and other nonferrous metals and for

painting wood in exterior weathering environments. Because they are also VOC compliant, acrylic latex coating systems have gained popularity as shop-applied systems. Even more popular are latex emulsion intermediate and/or finish coats used in conjunction with a water-based, inorganic, zinc-rich primer. Water-based, zinc-rich primers, coated with acrylic emulsion intermediate and top coats, are rapidly becoming popular because of their VOC compliance, good corrosion protection, and aesthetic properties. Although many of the acrylic emulsion coating formulations have dramatically improved moisture resistance, these coatings are not recommended for use in areas of high condensing humidity, ponding water, splash zones, or for immersion service. The ionic surfactants used in the emulsion to provide in-can stability will result in water sensitivity after application. Water vapor transmission may be a problem for wood or masonry surfaces, and latex paints may be suitable for these surfaces because they are said to breathe. Breathing occurs as a result of irregularities during the coalescence part of film formation. A series of pores or defects in the coalesced film allow passage of water vapor but retain the larger liquid water molecule. Water-based paints develop poor film properties when applied in cold, damp weather. Both cold weather and high humidity or dampness retard water evaporation and the drying and coalescence of the paint film. The result can be a soft, poorly adherent film that, when drying finally occurs, may be cracked or brittle with poor adhesion. Too fast a water evaporation rate on a hot surface can lead to a powdery, poorly adherent paint or a film with many voids, pinholes, or cross-sectional porosities. Storing emulsion paints at excessively high temperatures for prolonged periods or freezing the emulsion may destabilize it and cause settling, de-emulsification, and/or severe viscosity changes.

e. Bituminous (solvent evaporation). Bitumens used in the coatings industry are coal tar and asphalt. These materials are distinctly different physically and chemically; but in appearance they are essentially identical black, thermoplastic, tar materials. Coal tar enamels, or pitches, are derived from the coking of coal. When coal is heated in the absence of air to a temperature of approximately 1093 °C (2000 °F), it decomposes partially into a gas and a coke. Coal tar is formed when the gas is subsequently condensed. Lighter oil fractions are removed from the tar by subsequent heating and gas extraction until the desired coal tar composition for use in coatings is obtained. Asphalt may be mined or obtained as a residue from the distillation of crude petroleum. Lighter fractions are removed during distillation until the desired asphalt tar suitable for coating use is obtained. Asphaltic coatings have much greater UV resistance than the coal tars, and they are suitable for use in above-grade atmospheric weathering applications. However, coal tar coatings are vastly superior to asphaltic coatings in

moisture and chemical resistance. Because of UV light-induced cracking, unmodified coal tar coatings most commonly are used below grade or in water-immersion service. Thermoplastic bituminous coatings are applied as hot melts, solvent cutbacks, or water emulsions.

(1) Hot melt. Hot melt application involves heating the bitumen to a temperature of approximately 178 °C (350 °F) to 246 °C (475 °F); its viscosity at that temperature is low, almost waterlike. The hot melt then is applied by mop or swab to the surface being coated, although other techniques such as brush, rolling, or spraying may be used. Flow coating of the interiors of pipes and small vessels also is possible. In this method, the hot melt is flowed onto the pipe or vessel while the item is rotated or turned. In general, hot melt applications provide the best moisture and chemical resistance, followed in order by solvent cutback and water emulsions. Pipelines coated with hot melt coal tar have 100-year successful exposure experience underground and in water immersions. In the pipe coating shop, the pipe is blast-cleaned to SSPC-SP 10 metal by a rotary blast machine. The bitumen is flow-coated onto the pipe with alternate reinforcement of asphalt- or coal tar-impregnated felt paper. The finish wrap is of kraft paper for UV protection. Field application of a hot bitumen is best done by swabbing with a mop. However, swabbing is rarely done at present because of safety considerations and the development of suitable, safer, alternate coatings that are more easily field applied.

(2) Solvent cutback. Asphaltic or coal tar bitumens are dissolved in a suitable solvent (aliphatic and aromatic hydrocarbon solvents). Dissolving the bitumen in a solvent lowers its viscosity enough that the cutback can be applied by brush, roller, or spray as appropriate. After application, the solvent volatilizes and the bitumen resolidifies into a film. The coating thickness and moisture resistance of a solvent cutback is considerably less than that achieved by hot melt application, but the convenience of not having to heat the bitumen at the jobsite immediately prior to application is a major advantage. Cutbacks are used on pipelines, pump stations, below grade, and immersion applications when hot melt bitumens cannot be applied.

(3) Water emulsion. Water emulsions are prepared by suspending minute particles of the bitumen in water using emulsifying agents. Pigmentation with inert fillers such as coal dust, powdered silica, mica, and limestone dust may be incorporated with the bitumen. After application, the water evaporates and coalescence occurs to form a protective film. Latex emulsions (both asphaltic and coal tars) are widely used as driveway or parking lot sealers and as waterproofing agents. Bitumen latex emulsions are VOC compliant. Some solvent cutback applications may not be VOC compliant

because of the use of solvents; and hot applied, hot melt bitumens may release VOCs into the atmosphere during heating and application. Furthermore, volatile phenol-containing compounds produced during the heating of the bitumen are considered carcinogenic and skin irritants. Accordingly, suitable worker protection must be provided in the form of protective clothing and appropriate respirators.

f. Vinyl (solvent evaporating copolymer). Most vinyl coatings consist of a resin comprised of a copolymer of PVC and polyvinyl acetate (PVA) in the ratio of approximately 86 percent PVC to 13 or 14 percent PVA. Approximately 1 percent or less maleic acid is used as a modifier to provide adhesion to metallic surfaces, and the same amount of hydroxyl modification (using a vinyl alcohol) provides adhesion to vinyl butyral wash primers or other organic coatings. Increasing hydroxyl modification of vinyl chloride or vinyl acetate resins enables the incorporation of the vinyl into alkyds, epoxies, and other resin systems. This incorporation improves air dry, moisture resistance, and compatibility. Maleic acid modification to the vinyl chloride-vinyl acetate copolymer improves adhesion to blast-cleaned steel, zinc-rich coatings, or other metal surfaces. Additionally, the carboxyl groups introduced into the vinyl copolymer resins provide points of reactivity for crosslinking reactions.

(1) Vinyl chloride. Vinyl acetate copolymer coatings have been used extensively by USACE for protection of submerged steel or as a coating systems specified for the protection of steel used in locks and dams. Because of the high amounts of solvents that must be used to dissolve vinyl resins, most vinyl coatings, except water-based vinyl formulations, are not VOC compliant.

(2) Vinyl butyral wash primer. Basic zinc chromate vinyl butyral wash primers have been used extensively as primers to provide excellent adhesion to a variety of surfaces, including carbon steel, stainless steel, zinc, cadmium, tin, aluminum, galvanized steel, magnesium, and even glass. These wash primers are preferred when exposure to salt water or salt spray occurs because they inhibit underfilm corrosion. Basic zinc chromate and vinyl butyral wash primers formulated in accordance with DOD-P-15328 D incorporating a vinyl butyral resin, basic zinc chromate pigments, and a phosphoric acid alcohol solvent system have been used extensively in the past. For best performance, wash primers should be topcoated with a coating based on a hydroxyl modified vinyl solution resin. This is an especially effective system in seawater and freshwater immersion and in corrosive environments. Wash primers have many application particularities. If an all-vinyl system is desired, the wash primer must be coated with a hydroxyl modified vinyl solution coating. The maleic acid

modified vinyl resin coatings in common use in USACE will not adhere to the wash primer. Many other coatings adhere well to the wash primer, including oil-based alkyds, epoxies, and urethanes. When mixing, the acid diluent must be added slowly to the base with agitation to prevent local gelation. These wash primers should be used within 8 hours after mixing; any primer remaining after 8 hours should be discarded because there will be a gradual decline in adhesion of the mixed wash primer. There may be no physical change in appearance after 8 hours but adhesion will be diminished substantially. The mixed wash primers must be applied thin (as a "wash") to a thickness not exceeding approximately 1.9 cm (3/4 mil). Coating failures may result if mixing and application instructions are not followed. Vinyl wash primers range in VOC content from 680 to 765 grams/liter (g/L) (5.7 to 6.4 lb/gal). (To convert grams per liter to pounds per gallon, divide by 119.8, for example, $250 \text{ g/L} \div 119.8 = 2.1 \text{ lb/gal}$).

(3) Vinyl chloride-vinyl acetate copolymers. These vinyl solution coatings are noted for outstanding toughness and water resistance. USACE has used a five-coat vinyl system for years on steel exposed in both freshwater immersion and atmospheric service on locks and dam gates. Although the five-coat system is somewhat expensive to apply, it is extremely durable when properly applied. Repainting intervals of more than 20 years are commonplace, although maintenance repainting and touchup of deteriorated or damaged paint may be necessary at more frequent intervals. The common USACE vinyl system uses a vinyl resin containing 86 percent polyvinyl chloride, approximately 13 percent polyvinyl acetate, and maleic acid modification. The coating system has excellent toughness, moisture resistance, and light resistance; and it can be topcoated easily after extended periods of time. Generally, PVC-PVA copolymer coatings range in VOC content from 540 to 650 g/L (4.5 to 5.4 lb /gal).

(4) Waterborne vinyl. Vinyl resins and modified vinyls frequently are emulsified vinyls modified with acrylic resins to provide enhanced flexibility, toughness, and recoatability. Vinyl acrylics are most commonly used for exterior surfaces. Waterborne vinyl coatings consisting of pigmented polyvinyl acetate are formulated for interior use. The polyvinyl acetate can be used alone as a homopolymer, or it can be coreacted with other monomers such as the lower molecular weight esters of acrylic, fumaric, or maleic acid. Latexes based on polyvinyl acetate generally have relatively poor moisture resistance, light fastness, and exterior durability. They are not the preferred choice for exterior surfaces, although they are eminently suitable for interior use. Polyvinyl acetate based homopolymer and copolymers are relatively inexpensive, and they are easy to apply and clean up. These emulsion coatings are suitable for

interior use and exterior nonaggressive environments. However, an acrylic modification is required when greater moisture and exterior weathering resistance is needed.

g. *Catalyzed epoxies (crosslinking copolymers).* The epoxy resin most commonly used for industrial protective coatings is of the glycidal-ether type, specifically, that derived from bisphenol-A and epichlorhydrin. This combination of raw materials yields a series of related compounds that, prior to crosslinking, have an epoxide group at each end of the molecule, and an alcoholic hydroxyl group as a midchain pendant. Crosslinking takes place preferentially through the terminal epoxy groups then through the midchain hydroxyl groups. Other epoxy resins have been developed, including cycloaliphatic epoxies, that offer improvements in light stability and UV light degradation; but these epoxy resins do not exhibit the adhesion, chemical resistance, and flexibility of resins derived from epichlorhydrin and bisphenol-A. Epoxy cresol novolacs also have been developed and provide high temperature resistance and great chemical resistance at the expense of brittleness and a lack of toughness and flexibility. The epoxy molecules, particularly those of the bisphenol-A type, are relatively small and must be coreacted with copolymer curing agents to attain crosslinking properties sufficient to provide a protective coating. The copolymer crosslinker frequently is called a catalyst or curing agent, and it usually is a polyamine- or polyamide-containing material.

(1) Polyamine curing agents for epoxies. The polyamines (i.e., diethylenetriamine, hydroxyethyldiethylenetriamine, bishydroxydiethylenetriamine) are relatively small molecules with a low molecular weight compared to the epoxy resin. When reacted, they lead to tight crosslinking and high chemical and moisture resistance. However, during the crosslinking reaction, any unreacted amine may be squeezed out of the crosslinked film to the surface and develop the so-called amine blush, a hazy white coloration on the coating surface. The blush, a reaction between the amine and carbon dioxide from the air, is not detrimental and can be allowed to remain on the surface unless topcoating is necessary. However, the blush must be removed by wiping or washing it from the surface (it is water soluble) before a subsequent epoxy coat is applied. To minimize formation of the amine blush, many formulators require a 15- to 30-minute induction time after mixing prior to application. This allows the reaction to begin and initial crosslinking to occur before the paint is applied. Some of the small amine molecules will partially crosslink with the epoxy resin molecules and increase their size and reduce the tendency for migration.

(a) Polyamine crosslinked epoxy coatings generally have excellent alkali resistance and the greatest chemical resistance of the epoxies. They also have good moisture and water resistance. These epoxies are the most brittle and the least flexible; and they have a strong tendency to degrade on UV light exposure, resulting in chalking. Amine-cured epoxies, with suitable nonreactive pigments, are used widely as tank lining systems for the protection of steel and concrete in water and aqueous chemical immersion service. Because of their high crosslink density (achieved as a result of the small molecular size of most of the amines used as coreactants), amine-cured epoxies are the epoxies of choice in atmospheric or immersion environments of high and low (pH 3-12+) hydrolyzing chemicals.

(b) Phenolic modification to the epoxy resin further enhances water resistance; and phenolic modified epoxies, with amine coreactants, are perhaps the most popular coating system for freshwater and saltwater immersion and many aqueous chemical solutions, even at elevated temperatures. Phenolic modification enhances moisture and heat resistance properties of the epoxy, but it imparts slightly more brittleness and diminishes alkali resistance.

(c) Polyamine crosslinked epoxy coatings are readily formulated as VOC-compliant coating systems as a result of the low molecular weights of both the amine and epoxy coreactants. If a relatively low molecular weight bisphenol-A epoxy is used, both the epoxy and amine coreactants are in liquid form. Little if any solvent is needed to dissolve or dilute the resins, and 100 percent solids coatings are feasible.

(d) Amine adduct epoxies were developed to reduce the tendency toward amine blushing; to eliminate an induction time; and to make the low molecular weight amine less volatile, safer, and easier to mix. An amine adduct is prepared by reacting an excess of a polyfunctional (three or more reactive sites) amine with some of the epoxy resin to increase its molecular size. The prereacted amine adduct then is packaged in a separate container, sometimes with additional pigment and solvent. As with all other coreactant curing agents, the components in the separate containers are mixed prior to application. Because of the greater molecular size of the amine adduct relative to the unprereacted amine, amine blush is eliminated and most of the other problems associated with small molecular weight amines are minimized. Chemical crosslinking in the applied film is not considered to be as extensive as that provided by the nonprereacted amine, and the chemical resistance is somewhat less. However, application is much easier and not nearly as dependent on thorough mixing and adequate induction time.

(2) Polyamide curing agents for epoxies. Polyamide curing agents are the condensation products of a dimerized fatty acid with the polyamine. Terminal amine functionality allows crosslinking to occur as with a straight amine, although the polyamide molecule is much larger. The crosslinked film has improved flexibility, improved gloss and flow, excellent water resistance, and good chemical resistance. However, polyamide-cured coatings have somewhat less solvent and alkali resistance than amine- and amine-adduct-cured epoxies. Because fatty acids have a water repellent tendency, polyamide-cured epoxies are said to be tough, flexible, water-repellent coatings. Compared to the amine and amine-adduct types, polyamide-cured epoxies have significantly better UV light resistance, resulting in substantially less chalking on exterior exposure. Polyamide-cured epoxies are perhaps the most widely used of the three types of curative systems, and they have wide application in the protection of steel and concrete in freshwater and saltwater immersion. Polyamide-cured epoxies have the best exterior weathering resistance and the best ability of the epoxies to recoat after extended periods. Polyamide epoxies are used to protect substrates exposed to condensation and high humidity. Specially formulated polyamide-cured epoxies have the ability to displace water from a surface. These coating materials can be applied and cured under water to form corrosion-resistant coatings.

(3) 100 percent solids epoxies.

(a) The 100 percent solids epoxies can be formulated from low molecular weight polyfunctional liquid epoxy resins. The viscosity of these resins can be lowered even further by the use of compatible reactive diluents with an epoxy functionality of one; they do not contribute to crosslinking but are chemically bound into the final crosslinked film. The liquid epoxy resin system is crosslinked by a liquid polyamine or polyamide without the addition of any solvent. A tertiary amino phenolic catalyst, such as tri-(dimethylaminomethyl) phenol may be added to produce polymerization of the epoxy resin with itself. This and other phenols act as accelerators in the curing reaction. Silicone resins may be added as flow agents, and dibutyl phthalate can be added as a plasticizer. Thus, the entire liquid paint can be converted to a crosslinked coating that becomes a 100 percent solids epoxy. These materials have little, if any, volatile organic material so they are VOC compliant. Coatings formulated in this fashion show typical epoxy finish properties; but they are less flexible than other epoxies because the films are thicker and the close spacing of the reacting groups leads to a high crosslinked density. The film is tough and relatively nonbrittle. Solventless epoxy systems have low internal stress and are less brittle because there is negligible volume contraction on curing to a solid.

(b) The 100 percent solids epoxies generally have short pot lives because the coreactants are not diluted. Some formulations require the use of special twin-feed airless spray equipment for external mixing (refer to paragraph 8-2g). When aromatic polyamines are used for curing, hardening times of 4 to 12 hours can be attained even at temperatures as low as freezing. Although these coating systems are relatively expensive, they are used primarily as corrosion-resistant linings for storage tanks (e.g., oil tankers), both on land and in marine vessels. Because of their low molecular weight liquid formulation, these materials also can be used as self-leveling epoxy flooring systems. These coating systems generally are clear or high gloss and, when applied, have a waterlike consistency that hardens to a smooth, glossy flooring.

(4) Coal tar epoxies.

(a) Coal tar epoxy is a combination of a coal tar and an epoxy resin. The epoxy resin usually is packaged separately from the curing agent, which frequently is combined with the coal tar resin. The curing agent may be an amine, amine adduct, or polyamide. The crosslinking reaction is the same as those previously described, with active hydrogens from the amine nitrogen providing a crosslinking site to the epoxide groups and, in some situations, the hydroxyl groups of the epoxy resin. The coal tar acts as a filler within the crosslinked epoxy matrix, and the resulting film has the toughness, adhesion, UV resistance, and thermal stability of the epoxies combined with the extremely high moisture resistance afforded by the coal tar. The amine-cured coal tar epoxies generally have great chemical and moisture resistance but are more brittle and harder to apply and topcoat than the amine adduct and polyamide-cured coal tar epoxies. The polyamide-cured coal tar epoxies are more water resistant, flexible, easier to topcoat, and more tolerant of application variables than the other epoxies.

(b) One problem with coal tar epoxies is recoating. The recoat window for application of a coal tar epoxy topcoat to a coal tar epoxy undercoat can be as little as 18 hours with some formulations, and with most formulations it usually is within 48 hours. Extensive intracoat disbonding may occur after this time. The disbonding is believed to result from low molecular weight hydrocarbon oils from the coal tar exuding to the surface after application and from UV light-induced oxidation. Amine-cured coal tar epoxies are more susceptible to this phenomenon than the amine adduct and polyamide types. However, even with the latter types, the first coat may cure so hard and glossy after only a few hours that adhesion of subsequent coats may be a problem. To attain adhesion between an undercoat and subsequent coats of a coal tar epoxy, it may be necessary to roughen the surface by sweep blast cleaning or other scarifying

techniques and to remove the oxidation and exudate products. Alternately, slow evaporating strong solvents such as methylene chloride and diacetone alcohol can be applied to the coal tar surface being overcoated. These solvents will penetrate, attack, and partially dissolve or swell the coal tar epoxy surface so molecular entanglement and adhesion may occur. However, because these solvents are slow evaporating, they may be retained within the coal tar epoxy film. If the coal tar epoxy is immersed in water, these relatively polar solvents may attract water and blistering may occur. Therefore, care should be taken when using solvents to increase intracoat adhesion for coal tar epoxies in immersion service. The problem is of much lesser consequence if the coal tar epoxy is used on an atmospheric or nonwater immersion surface.

h. Urethanes (crosslinking copolymer). Crosslinking reactions in urethane coatings consist of a reaction between an isocyanate containing (-N=C=O) material and a material with a polyhydroxylated (-OH) containing coreactant. Crosslinking occurs because of the high reactivity and affinity of the isocyanate group for the active hydrogen of the polyolhydroxyl or any other active hydrogen atom attached to a nitrogen or oxygen atom. The rate of this crosslinking reaction depends on a number factors, such as the type and configuration of both the isocyanate and polyol materials and temperature. However, the reaction is such that, with most formulations, crosslinking can occur at temperatures as low as 18°C (0°F) or less.

(1) Isocyanates. The isocyanate reactant can be either aromatic (containing the benzene ring) or aliphatic (straight chain or cyclical) hydrocarbons. Aromatic polyurethanes are prone to darkening and yellowing on exposure to sunlight because of the chromophoric nature of the benzene ring. Because aliphatic polyurethanes, by definition, do not contain the benzene ring, they do not yellow or darken and are preferred for exterior use.

(a) The most important monomeric diisocyanates used for coatings are toluene diisocyanate (TDI), 4,4-diphenylmethane diisocyanate (MDI), and 1,6-hexamethylene diisocyanate (HDI). Because of their irritant characteristics, these materials rarely are used in unreacted form for the compounding of urethane coatings. They normally are converted into isocyanate terminated polymers or adducts of polyols such as hydroxyl terminated polyesters and polyethers. The molecular weight of these isocyanates can be increased by self-reaction in the presence of catalysts to form dimers and/or trimers.

(b) Aliphatic isocyanates react more slowly and are considerably more expensive than the aromatic isocyanates, but they allow the formulation of nonyellowing, light stable,

high gloss finish coats. The appearance of polyurethane coatings formulated with aliphatic isocyanates are unsurpassed in this regard by any of the epoxies, acrylics, or other coating materials. One of the most important aliphatic isocyanates is HDI. In its monomeric form, HDI is an irritant as is true with TDI and MDI. However, HDI can be reacted (commonly with water) to obtain a higher molecular-weight modification that is less volatile and safer. When HDI or its higher molecular-weight modifications are reacted with a suitable polyol in the presence of certain metal catalysts (tin, bismuth, zinc, iron, cobalt), a urethane coating with excellent resistance to discoloration, hydrolysis, and heat degradation is produced.

(c) Because of the potential presence of unreacted monomeric forms of TDI, MDI, and HDI—all of which are respiratory irritants—an air-fed respirator should be used when mixing and applying these materials. Workers and painters may never develop an isocyanate sensitivity, or the sensitivity may occur only after prolonged exposure. However, some individuals may become sensitized quickly, on initial contact or on only a short exposure. When isocyanate respiratory sensitization occurs, it occurs suddenly and drastically, and the affected individual should be removed from the work site. The sensitization is permanent, and increased exposure leads to increased irritation to affected tissues and membranes (refer to Chapter 10).

(2) Polyols. Polyols coreact with isocyanates to form a polyurethane film. A polyol consists of large molecules (commonly acrylics, polyesters, polyethers, epoxies, vinyls, and alkyds) that have been reacted with di- or polyfunctional alcohols such as propylene glycol, trimethylolpropane, pentaerythritol, and others. The hydroxyl-terminated polyol materials are packaged separately from the isocyanate, and the packaging usually includes appropriate solvents and pigments. On application, the isocyanate and polyol constituents are mixed and crosslinking proceeds via the isocyanate-hydroxyl functions and liberates a carbon dioxide gas. To prevent bubbles and voids in the coating cross-section as a result of the carbon dioxide gas inclusion, all polyurethane coatings must be applied relatively thin (0.038 to 0.05 mm [1.5 to 2.0 mils] per coat). This allows the gas to pass easily from the coating before the coating cures and hardens. In general, the characteristics and properties of the urethane coating depend predominantly on the properties of the polyhydroxylated coreactant. The VOC content of most polyurethane coatings ranges from 250 to 550 g/L (2.1 to 4.6 lb/gal).

(3) Acrylic urethanes. Acrylic urethanes are perhaps the most widely used urethanes for corrosion protection and

atmospheric service. When properly formulated, these materials have excellent weatherability, gloss, and color retention and good chemical and moisture resistance. They can be tinted easily and pigmented to provide a variety of deep and pastel colors at a lower cost per gallon than the next most popular class, the polyester urethanes. Acrylic urethanes are not used for water immersion service and, for the most part, they do not have the chemical resistance of the polyester urethanes. However, they have excellent weathering and color retentive properties when an aliphatic isocyanate coreactant is used. These are the most popular aliphatic polyurethanes; they are widely used as topcoats over epoxy primers and intermediate coats in most nonchemical atmospheric environments. Many water tanks, bridges, railroad cars, aircraft, and other highly visible structures are coated with these light-fast, glossy, aesthetically appealing coatings.

(4) Polyester urethanes. As a result of their high isocyanate demand when coreacted, polyester urethanes form relatively hard, chemical-resistant poly films. Because they are tightly crosslinked, they have great chemical and moisture resistance; but they are not as flexible and tough as the acrylic urethanes. This high isocyanate demand also substantially increases the cost of polyester urethane over acrylic urethanes. Polyester polyurethanes are used in exterior chemical environments in which acid fumes or highly corrosive conditions are encountered. They have high gloss, are light fast, and have a good appearance.

(5) Polyether urethanes. The polyether prepolymer is considerably less expensive than either acrylic or polyester polyols. However, polyethers are sensitive to UV-induced oxidative degradation. Ether linkages within the polyether are somewhat water sensitive; and, in polyethers, they are repeated throughout the polymer chain without separation by long water-insensitive hydrocarbon chains or aromatic groups. Polyester polyurethanes are used as elastomeric urethane coatings, for coal tar urethanes, and for other urethane coatings that are sheltered or protected from light. They frequently are used as pipeline coatings or for below grade corrosion protection, and coatings for minimum service.

(6) Epoxy polyurethane. Epoxy urethanes are considerably more expensive than conventionally cured amine or polyamide crosslinked epoxies. The epoxy addition induces a tendency for an epoxy urethane to chalk, and the lower moisture resistance resulting from the urethane crosslink produces a less chemical- and moisture-resistant polymer than a conventionally cured epoxy coating. Most epoxy urethanes are formulated with a less expensive aromatic isocyanate. They are promoted primarily as low-temperature-curing epoxies; as fast curing, chemically

resistant urethanes for interior use; or as primers in exterior exposures.

(7) Vinyl polyurethanes. Urethane coatings using vinyl polyols combine abrasion resistance of the urethane with the toughness, flexibility, and chemical resistance of the vinyl. These urethane coatings are promoted for use when flexibility and abrasion resistance are important. However, vinyl urethane coatings are subject to some chalking or fading on exterior exposure and do not have the color, gloss, weatherability, or solvent resistance of the acrylic and polyester urethanes. Because the vinyl is thermoplastic and is attacked and softened by solvents, recoating after extended periods is not a major problem and is a primary advantage of vinyl urethane systems. Coatings based on these resins are used on structural steel, ships, tanks, and other steel structures for which corrosion resistance flexibility and abrasion resistance are important.

(8) Moisture-cured polyurethanes. Isocyanates can react with the hydroxyl group in water (H-OH) to form a unique class of coatings known as moisture-cured urethanes. Single package moisture-cured urethanes use an isocyanate prepolymer that, when applied, reacts with the humidity in the air to form a tough, hard resinous film. Because of their rapid rate of reaction, aromatic isocyanates are used almost exclusively in moisture-cured urethanes. The pigments must be essentially nonreactive with the isocyanate. Although it is possible to use a number of pigments, aluminum leaf is common. Properly formulated and applied, urethanes have excellent adhesion to blast-cleaned structural steel surfaces. When spray applied, urethanes form a tough, glossy, highly protective chemical and solvent-resistance film. Because of their high crosslink density, the recoat window of some formulations is less than 24 hours, or it may be more than a month in exterior environments. Sufficient solvent hardness and permeability does not occur in 24 hours, and topcoating is considered safe. Topcoating is also safe after a month or more of exterior chalking and weathering to remove the slick, glossy surface that often occurs shortly after curing. However, within the range of 24 hours to a month or more, subsequently applied polyurethane topcoats may exhibit disbonding or poor adhesion. Moisture-cured urethanes are used as primers under some epoxies, used as full system coating on steel and nonferrous metals, and as primers on marginally cleaned steel. Frequently, the moisture-cured polyurethane primer and/or intermediate coats are topcoated with a nonmoisture-cured aliphatic polyurethane to minimize yellowing and darkening.

i. Vinyl ester (crosslinking copolymer).

(1) Strictly speaking, vinyl esters can be called vinyls because of the vinyl unsaturation ($-C=CH_2$) on the epoxy

backbone chain; actually, they are manufactured from and are closely related to acrylics. Methacrylic esters of bisphenol-A or other epoxies, such as novalacs, are prepared by reacting methacrylic acid with terminal oxirane groups of the epoxy. The resins have high viscosity at room temperature and are mixed with monomeric styrene, which acts as a reactive diluent to reduce viscosity. Crosslink curing is by free radical initiation generated from peroxide degeneration using benzyl peroxide, methyl ethyl ketone peroxide, or peroxide blends.

(2) Compared to normal unsaturated polyester resins, vinyl ester resins have better chemical resistance because of the stability of the epoxy backbone and the presence of stable methyl groups on the methacrylate terminations. Compared to a polyester resin, there are fewer points of unsaturation on the backbone, and even these are effectively shielded by methacrylate terminations. Vinyl esters have excellent resistance to acids and alkalies, bleaches, and other oxidizing agents. Vinyl esters are used as thick film (1.02 to 1.52 mm [40 to 60 mils]) tank and chimney linings when great strength and high chemical resistance are required. They most commonly are applied by spray, have a short potlife, and build readily to thicknesses approaching 0.50 mm (20 mils) per coat. Because of their short potlife and high chemical and solvent resistance, topcoating after even a short period of time (as little as 3 or 4 days) may be a problem with some formulations. Because the coatings are applied so thick and because of high inherent shrinkage stresses on curing, a deep anchor pattern (0.10 to 0.13 mm [4 to 5 mils]) is required for most applications. Care must be taken to ensure that the coating is not applied excessively thick, or cracking may occur.

(3) Vinyl ester coatings can be applied as highly pigmented, sprayable coatings or with a fiberglass veil reinforcement as fiberglass reinforced plastic laminants. Vinyl ester coatings have excellent abrasion and wear resistance, and these attributes combined with their chemical resistance lead to application as high build monolithic concrete floor systems and tank linings. Because of their high volume solids content and because styrene is used as a reactive diluent (combined thinner and coreactant), little thinner is required in a formulation. Thus, vinyl ester coatings are VOC compliant.

4-4. Drying Oils

a. If a drying oil is reduced or dissolved in a solvent and pigmented, a drying oil coating results. Not all oils are drying oils. An oil is classified as drying if, when spread out in the air as a thin layer, it changes from a liquid to a solid film with a great strength, toughness, and hardness. This drying ability depends on the molecular structure of the

various chemical compounds that make up the oil. Specifically, the oil must have polyunsaturated fatty acids, commonly ethylenic carbon double bonds ($-C=C-$). When combined with oxygen and accelerated by metallic driers, auto-oxidative polymerization occurs and transforms the oil from a liquid to a solid. Some vegetable oils (e.g., cottonseed, rapeseed, peanut, and coconut oils) are not drying oils. Fatty vegetable oils that exhibit proper drying oil characteristics and can be formulated into paints or protective coatings include linseed, tung, soybean, dehydrated castor, oiticica, and fish oils. Linseed oil, one of the most widely used drying oils, is obtained from pressing the flax seed. Raw linseed oils dry too slowly for most purposes; therefore, they require processing and the addition of driers to hasten the hardening rate.

b. Processing usually consists of heating the raw oil and dissolving mixtures of manganese and cobalt driers—which are soluble in the oil at ordinary room temperatures—in the raw oil. The oil can be further treated by bodying, which consists of blowing gases (oxygen and/or hydrogen) through the oils to increase viscosity and reduce drying time. All of these treatments (heating, blowing, and adding driers) result in an increased oil viscosity that occurs as a result of auto-oxidative crosslinking polymerization and oxygen absorption into the oil film. In general, bodied oils (those that have been thickened by heat treating and blowing air through them) dry more quickly, are tougher, and have better water, chemical, and after-yellowing resistance than untreated, unbodied oil. However, bodied oils do not wet and penetrate as well. Even if blown or bodied, drying oils may have their properties enhanced considerably by the addition of a synthetic resin. When added to the processed and treated drying oil, synthetic resins (e.g., alkyds, phenolics, epoxy esters, or urethanes) enhance the chemical and moisture-resistant properties of the drying oil.

c. Animal oils, principally menhaden fish oil, have properties similar to drying vegetable oils, except they are somewhat slow drying, become tacky in humid weather, and give off an unpleasant odor in confined spaces. Animal oils are not recommended for interior use, and they frequently are combined with other drying oils.

d. In a strict sense, oil paints consist of a pigment, a drying oil, and an aliphatic solvent used to thin the pigmented oil. The oil is not modified with any synthetic resins. The coating initially dries by solvent evaporation; this is followed by auto-oxidative crosslinking of the drying oil. The addition of driers to the oil aid in the formation of the solid film. The characteristics of these oleoresinous paints are determined primarily by the characteristics of the drying oil, and to a lesser degree by the pigments incorporated into that oil. Because these paints have a high

oil content, drying times are slow with 2- to 3-day recoat periods over the soft film. However, long oil paints were formulated for use over poorly prepared, rusted, and/or mill scale surfaces; so for these situations, long oil paints may be the best paints.

4-5. Driers

Driers are materials that promote or accelerate the curing or hardening of drying oil paints. Drying of oil-based paints by auto-oxidation is affected considerably by temperature and the presence of certain catalysts. Driers act as a catalyst to aid in both surface and through drying of drying oil paints. Driers are considered metallo-organic materials that can be classified as surface driers and through driers. The metal constituent is lead, cobalt, zinc, or manganese; the organic radical of the metallo-organic dryer is usually a naphthenate derived from naphthenic acid. Surface driers are compounds of cobalt and manganese. The use of these materials will cause a surface of the drying oil paint to rapidly set to a near solid, but the underlying paint does not reach this advanced state of oxidation. In thick films an uneven hardening will cause wrinkling; therefore, through driers should be used in conjunction with surface driers. Through driers are metallo-organic compounds of lead, cadmium, zinc, or zirconium. When used in conjunction with surface driers, through driers help cause auto-oxidative crosslinking through the cross-section of the film. Driers may lose their effectiveness with prolonged storage. This storage problem affects the primary surface driers (cobalt and manganese) and, to a lesser degree, secondary driers (calcium and zinc). The loss of dryer effectiveness is believed to result from the absorption and deactivation by certain pigments, notably carbon black. If an oil-based paint is aged, it may be best to test its ability to dry by applying some of it to a nonabsorptive surface to see if it dries properly.

4-6. Pigments

Virtually, all protective coatings used for corrosion protection contain pigments. Although the obvious purpose of pigmentation in a coating is to provide color and opacity, proper formulation of pigments into a protective coating does far more than that. For corrosion-protective coatings, pigments function by providing inhibition or passivation of a metal surface, preventing corrosion; reinforce the paint film; act as a barrier to provide water impermeability to the dried paint film; and with zinc-rich coatings, sacrifice galvanically to protect the underlying steel substrate (refer to Chapter 2). Certain pigment types enhance heat, abrasion, acid, or alkali resistance to coatings. Pigment particle size and shape, ease of wettability by the binder, and bulking or properties relating to specific density

contribute significantly to the viscosity and application characteristics of the wet coating and, ultimately, properties of the dried, protective coating.

a. Inhibitive pigments. A select few pigments provide active corrosion inhibition to metal substrates when formulated into a coating composition. These pigments are slightly water soluble; and, when the paint film is exposed to and permeated by moisture, the water in the film cross-section partially dissolves constituents of the pigment and carries it to the underlying metal surface. The dissolved ion species react with the metal (commonly steel or aluminum) to form a reaction product that passivates the substrate and reduces the rate of underfilm corrosion.

(1) Chromate. Chromate-containing pigments (e.g., zinc and lead chromates) partially solubilize, liberating the chromate anion that, when carried by moisture to the underlying steel or aluminum substrate, reacts to form a chromate film on the metal surface. This chromate film strongly passivates the metal surface and prevents establishment of electrochemical corrosion cells by reducing electron transfer. Additionally, this passivating film is slightly alkaline, which further inhibits underfilm corrosion. To a lesser degree, molybdate and borate pigments also provide active underfilm passivation, but not nearly as well as the chromate-containing pigments.

(2) Lead and zinc. Lead and zinc also may disassociate partially on moisture permeation into a paint; these elements also provide inhibitive protection, but in a different fashion. When pigmented into oil-based coatings, lead and zinc react with acidic degradation products that occur as a result of oxidation and UV light exposure. If these complex organic acids reach the underlying steel, under-film corrosion may be hastened. However, the lead and zinc cations react with the acids complexing, insolubilizing, and/or neutralizing them. Lead and chromate pigments are considered hazardous paint ingredients, and many coating formulators are restricting or eliminating these materials from their formulations. Although substitute pigments may be safer, they may not offer the inhibitive properties of the pigments they replace.

b. Barrier pigments. Barrier protection is offered to a greater or lesser degree by all inorganic pigments formulated into a coating. Any permeating moisture must migrate around the pigment particle and, by so doing, increase its permeation path length to the substrate. However, some pigment types are specifically formulated as barrier pigments, or alternately impart barrier properties to the paint film. Most notable of the barrier pigments is flaked aluminum.

(1) Aluminum flake. Aluminum flake, in the form of a leafing aluminum (coated with a stearic or other fatty acid to cause it to be displaced to the surface by the coating binder) or nonleafing flake (noncoated), is specifically added to many types of coatings, particularly oil-based coatings and epoxy mastic coatings to enhance UV light resistance and reduce moisture permeation. No other pigments can provide the leafing properties that aluminum flake does. Leafing aluminum pigments are widely used in alkyd finish coats to provide a bright, shiny appearance and for resistance to atmospheric weathering (UV) and moisture.

(2) Micaceous iron oxide. Micaceous iron oxide, commonly used in Europe and to a lesser degree in the United States, has lamellar (platelike) particles. Any relatively large sized pigment particle, even if it is not plate shaped, will increase the permeating path of moisture and result in a barrier-type protection. Some recently manufactured pigments consist of hollow glass spheres that have been developed to aid in VOC compliance and to fill a coating and make it more moisture impermeable.

c. Sacrificial pigments. High purity zinc dust, with little zinc oxide or carbonate contamination, is the only sacrificial pigment used in paint manufacture. These zinc dust pigments consist of particles that are of a relatively large (1 to 3 μ) diameter and are essentially pure zinc. If the zinc pigment particles are in contact with both each other and the underlying steel surface when incorporated with a binder into a dry paint film, galvanic protection results. On the galvanic series zinc is anodic to steel and becomes the anode in a zinc-steel galvanic couple. The zinc anode corrodes and dissipates, and the underlying steel cathode remains galvanically protected. This phenomenon occurs for all zinc coatings, including those deposited by hot dip galvanizing and thermal spraying. Thermally sprayed aluminum coatings (both aluminum powder and wire) also are believed to have sacrificial capability when applied to blast-cleaned steel. However, this sacrificial capability may last for only a short time—within a few days after application until the aluminum oxidizes sufficiently to insulate the aluminum from the steel. Galvanic protection ceases after a sufficient thickness of intact aluminum oxide forms on the sprayed aluminum coating.

d. Color pigments. A number of inorganic pigments provide color to paint. Titanium dioxide in both the rutile and anatase forms is the most popular white pigment because of its high refractive index and excellent hiding power (the ability to render a paint opaque). Rutile titanium has the highest refractive index and the best tinting strength of all other pigment types. (Tinting strength is the ease by which color pigments can be mixed with another pigment to color the paint.) Other pigments, both organic and

inorganic, frequently are used in combination with titanium dioxide to add color. Natural iron oxides range in color from a yellow to a bright brown red, to a greenish brown, and a deep rich brown. Synthetic iron oxides range in color from yellow and red to brown and black. Red chromate pigments with sulfate, and sometimes molybdate additions, range in color from a light yellow to a bright orange or scarlet red. Because of their bright, clean color, lead chromate pigments frequently are used in highway striping paints and in safety color paints. Even though lead chromate is considered hazardous, the pigments in these paints will be difficult to replace because no other pigments have a similar light fastness and brightness. The purpose of organic pigments is primarily to provide paint color. Originally, organic coloring pigments were extracted as colorants from insects and vegetables. Synthetic organic pigments now have been developed, but few of these have technical or commercial importance in corrosion-preventative coatings. Compared with inorganic pigments, organic pigments generally are brighter colored, have less hiding, are more prone to bleed, have much poorer heat and light fast resistance, and are substantially higher in price. The most important class of organic color pigments are called azo pigments and are manufactured from aromatic hydrocarbons, which are available from coal tar or petroleum distillates. These pigments are characterized by the presence of a chromophore consisting of one or two azo groups ($-N=N-$).

e. Hiding pigments. Pigments with a high light refractive index provide the best hiding. Rutile titanium dioxide, followed by anatase titanium oxide, zinc sulfide, and zinc oxide have relatively high refractive indices. Conversely, silica, whiting, and barytes all have relatively low refractive indices and do not provide good hiding when formulated into paints.

f. Extender pigments. Certain types of pigments do not provide inhibition or have good barrier or sacrificial characteristics. They do not have a high refractive index and do not impart good color or hiding to a paint film. However, as reinforcing pigments and flow control pigments, they are important in coating formulation. As a class, these pigments can be called extender pigments because they are relatively inexpensive compared to most other pigments; they are used in conjunction with more expensive pigments to reduce costs. The use of extender pigments reduces shrinkage stresses within the paint film, giving it strength, and "extending" the pigment volume content at relatively low cost. Extender pigments include those based on carbonates, silicates, sulfates, barytes, and mica. Each of these types of pigments is somewhat different, but they all are relatively low cost materials that can be added in finely divided form to a paint to aid in its

rheological properties (viscosity and flow control) and to reinforce the dry film strength.

4-7. Solvents

a. In a true sense, a solvent is defined as a substance, usually a liquid, that will dissolve and change a solid to a liquid state. In the coating industry, solvents are considered any volatile liquid formulated into a paint, even though it may not have solvency power. Some liquids are diluents and, even though the diluent may not have solvency power, it may enhance the solvency of other solvents in the paint. Water is the universal solvent, except for its use as a dispersant in emulsion coatings, but it is not used as a paint solvent in durable coatings. Water-soluble resins are susceptible to softening and swelling by water; therefore, coatings made from them will not be addressed in this manual. However, water-soluble resins should not be confused with water-emulsified resins, which were discussed earlier in this chapter. Organic solvents impart low water sensitivity and are the solvents of choice when dissolving solid resins.

b. The purpose of any solvent is to dissolve solid paint constituents, reduce viscosity, and render the paint fluid enough that it can be satisfactorily applied. The solvent is undesirable after application and must evaporate from the drying coating film. In addition to enabling application of the coating material, solvents must be able to wet the substrate being coated and penetrate into and help the coating seal any crevices, voids, or depressed irregularities. Also, the solvent must volatilize fast enough to prevent runs and sags in the drying coating film. However, a solvent that is too volatile can cause solvent pops, loss of gloss, dry spray, poor surface wetting and penetration, and poor film flow and inhibit cure. Virtually all coating formulations use a blend of solvents to achieve optimum properties. Some solvents within the blend will evaporate fast, enabling the drying paint to set quickly. Other solvents may dry slower and provide wettability and penetrability. Ultimately, all solvents should evaporate to allow the coating to achieve hardness, cure, and final properties. Solvents can be categorized according to their chemical composition. The most commonly used categorization subdivides solvents into classes called turpentine, hydrocarbons, ketones, esters, alcohols, and glycol ethers.

c. *Turpentine.* Turpentine solvents are actually hydrocarbon solvents; they are categorized separately because they are derived from southern pine trees as opposed to solvents fractionated from petroleum and coal tar refining. Turpentine is used infrequently today in manufacturing corrosion-protective coatings, although it is widely sold in retail paint stores for field thinning of oil-

based house paints and varnishes. Gum-spirits turpentine is distilled from crude gum rosin obtained by tapping southern pine trees. Wood turpentine has a somewhat different composition from gum turpentine and is obtained by distillation of the crude rosin extracted from the ground wood from southern pine stumps. Sulfate turpentine is obtained as a by-product of the Kraft paper industry. Turpentine has good solvent power for most oil and oleoresinous binders, but its use is limited in modern paint technology because of its relatively high price and slow evaporation rate. Other turpentine-like solvents, such as dipentene and pine oil, also are obtained from southern pine trees and have specialized uses.

d. *Hydrocarbon solvents.* Hydrocarbon solvents are obtained from both petroleum and coal tar sources. Petroleum hydrocarbon solvents are the lighter (more volatile) fractions from the distillation of crude oil. Coal tar hydrocarbons are distillation products from coke oven by-products. Hydrocarbon solvents may be classified as aliphatic or aromatic.

(1) *Aliphatic hydrocarbons.* Aliphatic hydrocarbons are straight or cyclical carbon-hydrogen containing liquids that are nonpolar in character and exemplified by mineral spirits, "varnish makers and painters" (VMP) naphtha, and other materials such as hexane and heptane. For the most part, these solvents have poor to moderate solvency for all but oil-modified coatings. Their solvency can be increased by blending them with various amounts of other, more powerful solvents such as aromatic hydrocarbons or ketones. Aliphatic hydrocarbons are generally the least expensive of all solvents and can be obtained in a wide range of evaporating rates. Aliphatic solvents are considered the least toxic of any of the solvent classes, although—as with any other solvent—gloves, respirators, and protective clothing should be used by individuals applying paints containing these solvents. Naphthenic hydrocarbons are aliphatic hydrocarbon solvents, but with a cyclical ring molecular structure. The naphthenic solvents are midway between the aliphatic and aromatic solvents in solvency power. Naphthenic solvents are used in alkyd and epoxy ester coatings and asphaltic and coal tar-containing coatings.

(2) *Aromatic hydrocarbons.* Aromatic hydrocarbon solvents contain a benzene ring structure. The most common solvents of this type are toluene (toluol), xylene (xylol), and high-flash naphtha. Aromatic hydrocarbon solvents have a greater solvent power than aliphatic hydrocarbon solvents. They generally are good solvents for oils, oleoresinous binders, alkyds, bitumens (asphalts and coal tars), and some synthetic resins. Aromatic solvents can be blended with more powerful solvents to enhance their power of solvency.

e. Ketone solvents. Ketones such as acetone, methyl ethyl ketone, methyl isobutyl ketone, and diacetone alcohol have varying evaporation rates and relatively strong solubility parameters. These solvents exhibit strong hydrogen bonding and high polarity. When retained in a paint film, they may attract and draw moisture into the coating. As with all other solvent classes, each of the ketone solvents has a different evaporation rate; care should be taken when using ketone solvents with slow evaporative rates to minimize solvent entrapment within the coating. As a class, ketones are polar materials characterized by exceptionally strong solvency for many resins used in protective coatings. They are used extensively as solvents for vinyls, urethanes, epoxies, and acrylics. Ketones usually are more expensive than ester-type solvents, but they are cost effective because the use of ketones allows for greater use of inexpensive aromatic diluents. As with all solvent families, solvency decreases as molecular weight and branching increase.

f. Ester solvents. Ester solvents contain the acetate functionality (-C-O-R). Ethyl acetate, isobutyl acetate, ethylene glycol, and monoethyl ether acetate are examples of ester solvents. They have solvency power between the aromatic hydrocarbons and ketones, but they have a high hydrogen bonding index and a relatively high polarity. Care should be taken to avoid solvent entrapment when using ester solvents. Ester solvents are strongly polar and are used as solvents for similarly polar resin film formers. The esters are characterized by a sweet, pleasant, strongly fruity odor. Ester solvents are used in cellulosic lacquers, urethanes, vinyl, epoxy, and acrylic coatings. Slow-volatilizing ester solvents are used as tail solvents in waterborne acrylic emulsions to aid coalescence and as tails in solvent-borne coatings to maintain solvency and reduce resin precipitation. Tail solvents are designed to be the last solvents to evaporate from a coating.

g. Alcohols. Alcohols are water miscible, and care should be taken when using them so water is not introduced into the coating. Alcohols are highly polar with a strong affinity for the water molecule. They are used to dissolve polar materials; and, when formulated into a coating, care should be taken to ensure that all alcohol will volatilize. Water miscibility and hygroscopicity are reduced as the alkyl group increases, and few alcohols above butanol (C₄H₉OH) have high miscibility with water. An exception is tertiary butanol, which—because of the compactness of the alkyl structure—retains complete water miscibility. The three most important alcohols are ethanol (denatured), isopropanol, and n-butanol. Methanol is toxic and is used only as a polar additive in paint removers because its low molecular weight serves it well as a penetrant. Alcohols are used as solvents for resins such as polyvinyl acetate, some

phenolics, vinyl butyral wash primers, most epoxies, and inorganic zinc-rich coatings based on ethyl silicate vehicles. Because of reactivity of the alcohol hydroxyl group, alcohol solvents cannot be used as solvents in polyurethane coatings. Alcohol is a solvent common to many epoxies. Chlorinated solvents such as 1,1,1, trichloroethane, chloroforms, dichloroethane and dichloroethylene, and methylene chloride, although used infrequently in paints, are good paint strippers, especially for epoxies and polyurethanes. Chlorinated solvents are nonflammable and VOC compliant because they generally are nonphotochemically reactive. However, they are toxic to humans and are environmental contaminants. These solvents should not be stored in, or used with, aluminum containers or equipment.

h. Glycol ether solvents. Glycol ether solvents, such as ethylene glycol monoethyl ether and ethylene glycol monobutyl ether, are a specific subcategory of the ester solvents. The most important solvent of this type has been ethylene glycol monoethyl ether (Cellosolve®¹) acetate. However, because of toxicologic considerations, this solvent largely has been replaced by propylene glycol monomethyl ether acetate, which appears to be less toxic. Glycol ethers are tail solvents for epoxies, vinyls, and urethanes. Glycol ether solvents are water-miscible and will attract moisture in buried or immersion conditions; therefore, care must be taken to ensure they completely volatilize from coatings to be used in immersion or below grade service. Anhydrous solvent grades are necessary if glycol ethers are used in urethane formulations. Glycol ethers are particularly good solvents for epoxy resins.

i. Solvent safety. Safety should be a consideration at all times when using solvents because all solvents are combustible and some are highly flammable. Solvents with lower molecular weight or faster evaporating rates usually are more flammable. Fast volatilizing, flammable solvents can lead to explosions, especially within confined spaces. All solvents are heavier than air and tend to flow downward; so, unless adequate ventilation and air movement are used, solvent vapors will collect and concentrate in low-lying spaces. Safety considerations are discussed in detail in Chapter 10.

4-8. Miscellaneous Additives

A number of miscellaneous compounds are added by the paint formulator to paints for specialized purposes. These include antiskinning agents, fungicides, thixotropes, UV light absorbers, plasticizers, flow agents, and emulsion aids.

¹ Union Carbide, Indianapolis, Indiana.

a. *Antiskinning agents.* Skinning sometimes occurs on storage of coatings containing drying oils. The surface of a paint dries and forms a skin on the paint surface in the can. When used excessively, driers have a tendency to aggravate skinning. To avoid skinning, antioxidants such as certain phenols and oximes can be added. The oximes, characterized by the reactive group ($-C=N-OH$) are by far the most commonly used antiskinning agents. Skinning is the result of the drier functioning properly, and it usually is not a problem in unopened or full cans. Antiskinning agents are volatile and accordingly, when using some of the paint in a can, close it tightly after use.

b. *Fungicides.* Fungicides or mildew inhibitors are added to paints to prevent mold growth. Mildew feeds on some components of a paint film, particularly oleoresinous vehicles, most latex paints, and some polyamide epoxies that offer a source of food. Mildew spores are omnipresent in air, will deposit on the paint, and, under the right conditions, will begin to grow. In the past, compounds based on phenyl mercuric and tributyl tin compounds were used as fungicides; but, because of their high toxicity, they have been replaced by complex organics such as carbamates, benzothiazoles, alkylisothiazolinone, chlorinated isophthalonitriles, and chlorinated adamantane complexes. However, the new materials have not attained the effectiveness of the older materials. Fungicides function in the can to kill organisms that might upset paint stability, which is particularly important in latex emulsion paints that can become rancid if microbiological growth is not stopped.

c. *Thixotropes.* Rheological coating properties such as film build, sag control, flow and leveling, and pigment settling properties can be adjusted through the use of thixotropic additives. Thixotropes can enable a rapid increase in the viscosity of a liquid coating material and allow it to build thicknesses over edges and plane surfaces and to resist sag. However, when mixing and applying the coating, shear stresses can break down the coating thixotropy rapidly, enabling it to be applied as if it were low in viscosity. Thixotropy recovers after application, and film build and antisag resistance again occur. There are a number of thixotropes that can be added to solvent-borne coating systems, including castor oil derivatives, high molecular weight polyolefins, montmorillonite and other clays, fumed silicas, fibrated minerals, calcium sulphonate derivatives, and others. Each of these classes has specific advantages and disadvantages with each of the binder systems in which they are incorporated. Similarly, thixotropes are important for waterborne systems to provide the same properties. The more common waterborne system thixotropes are nonionic cellulosic thickeners, polyacrylic acids and salts, anionic polycarboxylic acid-based thixotropes, and, more recently, a nonionic associative

thickener based on ethoxylated polyether-based urethane block copolymers. The nonionic thickeners give the most improved flow and leveling characteristics to water emulsion coatings, providing better gloss and semigloss paints. In roller applications, the nonionic thickeners result in a significantly reduced roller spatter. Thixotropes prevent hard settling of many heavy pigments, such as zinc. Most thixotropes deteriorate on aging, which causes variations in viscosity of the paint in the can. Some paints have increased viscosity; others may suffer a viscosity decrease.

d. *Flow agents.* The addition of flow agents enhances the freshly applied paint film's ability to flow out after application, eliminating brush marks, roller patterns, orange peel from spraying, and other film irregularities and defects. The flow rate of paint is affected by the rate of solvent release and solvent system evaporation. Surface tension and the coating's viscosity, which vary as a function of temperature, also affect the rate of flow or leveling of the applied paint film. Depending on the type of flow problem encountered, the generic type of coating, and the coating formulation, different flow and leveling agents are added in small amounts (usually less than one percent) to eliminate or minimize problems. Most flow agents function by increasing the viscous force in the coating, overcoming the paint's tendency to flow. Surfactants also help to overcome leveling problems by reducing surface tension.

e. *Emulsion aids.* Emulsion aids are used in waterborne paints and often are called surfactants. Proper use of surfactants enable a waterborne emulsion to remain in suspension and keep it from settling and packing at the bottom of a can during prolonged storage. All surfactants have a hydrophilic (water-loving) group and a hydrophobic (water-hating) group, which is water repelling. The hydrophobic group is usually in the form of a long hydrocarbon tail terminating in a simple long polar alkyl group. The hydrophilic group is usually a charged species such as an ammonia ion, a polar organic group (carboxylic acid), hydroxyl, sulfate, etc. The surfactant molecules containing both the hydrophobic and hydrophilic ends orient themselves around the emulsion particles to effectively separate them and keep them apart. However, prolonged storage at elevated temperatures, or freezing the emulsion, may destabilize it and cause separation and possible de-emulsification. A number of different types of surfactants can be used, depending on cost, solution, pH, and specific emulsion requirements. Emulsion chemistry is complex and, unlike formulating solvent-based paints, often requires considerable trial and error.

f. *UV absorbers.* UV light, particularly in the actinic region of 280 to 315 nm, can degrade exterior paint films. Incident UV light is absorbed by the paint, raising the paint

to a higher energy state. This causes bond cleavage and release of free radicals, which leads to depolymerization, chain scission, or, in some instances, crosslinking and embrittlement. This surface effect ultimately results in degradation of the coating at either the surface (as is generally true with epoxies that readily chalk) or the coating interior, if the coating is partially transparent to UV light energy. To prevent this, UV absorbers are added to the formulation at the rate of approximately 1 to 3 percent, by weight, depending on the type of coating, the degree of pigmentation, and the type of surface. Zinc oxide is an effective UV absorber, but it sometimes leads to embrittlement of oil-based coatings and may not be appropriate for other generic types of coatings. Most UV light absorbers are complex substituted aromatic compounds that absorb UV radiation strongly without being degraded. Hydroxy substituted benzophenones and benzotriazoles are used most commonly.

g. Plasticizers. Plasticization is a process of increasing the flexibility and adhesion of an organic coating film and decreasing its brittleness, cohesiveness, and glass transition temperature (the temperature at which a polymer changes from a flexible, rubber-like material to one that is hard and brittle). Plasticization can be achieved by chemically modifying the resin polymer or by adding compounds to the coating formulation. Chemical modification of the compound can be done by reducing crosslinking or by formulating resin molecules with bulky side chains to prevent parallel orientation and crystallinity. Alternately, external plasticizers (such as monomeric phthalates, phosphates, adipates, and sebacates), chlorinated paraffin, or biphenyls can be added to a resin system to soften it and lower the glass transition temperature. The plasticizing materials generally are relatively low molecular weight, slow-evaporating materials that, when mixed with a resin, soften it by preventing crystalline orientation and terminating crosslinking sites. The type of plasticizing agent used depends principally on the generic type and molecular weight of the resin system used in the coatings formulation. In time in some applications or service conditions (such as high temperature/humidity), low molecular weight plasticizers may migrate to the surface of the coating; and the surface may become sticky and attract and hold dirt. More importantly, the coating often embrittles, becomes less flexible, or shows surface or through-cracking.

4-9. Zinc-Rich Coatings

Zinc-rich coatings, or zinc-rich primers, are unique in that they provide galvanic protection to a steel substrate. As "rich" in the name implies, the binder contains a large amount of metallic zinc dust pigment. The binder can be an inorganic zinc silicate or an organic resin such as an epoxy,

butyl, or urethane. After the coating is applied to a thoroughly cleaned steel substrate, the binder holds the metallic zinc particles together and in contact with the steel. Thus, metal-to-metal contact of the two dissimilar metals is made and results in a galvanic cell. Zinc becomes the anode in this cell and sacrifices itself to protect the underlying steel cathode. Properly applied zinc-rich coatings, zinc galvanized coatings, and thermally sprayed zinc eliminate pitting and under-film corrosion even at voids, pinholes, scratches, and abrasions in the coating system. This cannot be said of any other type of coating, and this protective capability makes zinc-rich coatings unique and widely used (refer to Chapter 2).

a. Inorganic zinc-rich binders. All inorganic zinc-rich coatings require an extremely clean surface (SSPC-SP 10 or SP 5), or application over a clean, pickled surface. Because of their inorganic nature, inorganic zinc-rich coatings are highly resistant to scuffing, scraping, and mechanical damage. They have good dry heat resistance to temperatures as high as 399 °C (750 °F) and good resistance to immersion in oil, petroleum distillate products, solvents, fresh water, and many other neutral pH aqueous solutions. Some formulations are suitable for immersion in salt water; others are not. The high conductivity of salt water enhances corrosion of both the zinc and zinc pigment particles within the coating and the underlying steel. Therefore, the protective life of zinc-rich coating in saltwater immersion may not be as long as that in freshwater immersion. In atmospheric environments, inorganic zinc-rich coatings provide long-term corrosion protection in damp, humid environments and where chemical attack does not occur. Inorganic zinc-rich coatings can be applied to steel at thicknesses of from 0.05 to 0.09 mm (2 to 3.5 mils) to provide atmospheric and immersion corrosion protection and left without a topcoat for long periods of time. Salt contamination may be a problem in marine environments; and research and panel testing done by NASA have established that zinc-rich primers, particularly inorganic zinc-rich primers, protect longer without topcoats than the same primers with an organic topcoat. However, other studies for chemical and weathering environments have established that topcoating with an organic topcoat may increase coating system longevity. Both inorganic and organic zinc-rich coatings can be specially formulated as preconstruction primers. This type of primer is applied to ships, subassemblies, and other prefabricated steel. When the steel is fabricated, welding can be done without removal of the preconstruction zinc-rich primer. Topcoating inorganic zinc-rich coatings may be more difficult than with any other coating because of the inherent porosity of the zinc primer. The binder partially wets and adheres the zinc-dust particles together and to the underlying substrate, but it does not fully encapsulate or seal the surface. Therefore,

topcoats applied over the porous surface may displace entrapped air causing pinholes, bubbles, or voids within the topcoat cross-section. This problem is not nearly as prevalent when using organic zinc-rich coatings because the organic binder more thoroughly wets, encapsulates, and seals the porosity of the highly zinc-dust-loaded dry film. Inorganic zinc-rich coatings may be one of three major groups: post-cured water-based alkali metal silicates, self-cured water-based alkali metal silicates, and self-cured solvent-based alkyl silicates.

(1) Post-cured, water-based alkali metal silicates. Post-cured, water-based inorganic silicates come as a three-package system: zinc dust, silicate binder, and curing solution all packaged separately. The binder is an inorganic alkali metal silicate, usually of the sodium, potassium, or lithium family. Zinc powder is slowly mixed into the alkali metal silicate binder, and the resulting solution is spray applied with an agitated spray pot to keep the zinc-dust pigment in proper suspension. After water evaporation and hardening of the zinc silicate coating, a phosphoric-acid-based curing solution is sprayed or brushed over the surface to neutralize the alkali metal binder. The neutralization reaction and subsequent interactions with zinc and iron ions further neutralize the silicate alkalinity and insolubilize the film. The coating becomes insoluble to water and resistant to weathering exposure. Post-cured, inorganic zinc-rich coatings are believed to be the best performing of the inorganic zinc-rich coating materials because of their relatively complete, insolubilized, hard cure attained after application of the curing solution.

(2) Self-cured, water-based alkali silicates. The most common of these silicate binders is based on potassium and lithium silicates, or combinations. Lithium hydroxide-colloidal silica and quaternary ammonium silicate binders also can be used. The alkali silicate binder is partially dehydrolyzed so its high alkalinity is considerably reduced in comparison with post-cured, inorganic silicate vehicles. Therefore, after application, initial water evaporation, and insolubilization, sufficient neutralization and cure are attained by further reaction with atmospheric moisture and carbon dioxide. Carbon dioxide in the presence of atmospheric moisture forms a weak carbonic acid, which in time is sufficient to neutralize the alkalinity of the silicate binder. If a more rapid insolubilization or cure is desired, heat or an acidic curing solution can be applied. When final curing is attained, most water-based, zinc-rich coatings—whether post- or self-cured—experience a color change, usually from a reddish or light gray to a darker blue-gray.

(3) Self-cured, solvent-based alkyl silicates. The binders for these silicate coatings consist essentially of partially hydrolyzed alkyl silicates of the series methyl through hexyl or glycol ether silicates. Of these, the ethyl silicate type is

the most prevalent. After application and initial solvent drying, the coating system hardens; but to cure, hydrolysis with moisture from humidity in the air is required. The hydrolysis of the silicate binder liberates ethyl alcohol (or an alkyl alcohol if other alkyl silicates are used). The alcohol volatilizes, makes the hydrolysis reaction irreversible, and hardens and cures the binder. If the silicate binder is applied indoors or in an arid exterior environment, water may be sprayed onto the surface with a spray gun or a garden hose with a fine atomization. Two or three applications may be required over a 2- or 3-day period to obtain optimum curing of the binder. All inorganic zinc-rich coatings can attain VOC compliance because of their high solids content, but the water-based post- and self-curing alkali silicates have virtually no VOC release.

b. Organic zinc-rich binders. Organic zinc-rich coatings most commonly are formulated from epoxy polyamide, urethane, vinyl, and chlorinated rubber binders. Alkyds have been used for some air-dry formulations, but they most commonly are used with baking formulations, notably in the automotive industry. Drying, hardening, and ultimate curing of the organic zinc-rich coating is determined by the type of binder used. The hardening and curing mechanisms of the various organic binders have been described previously (paragraphs 4-2 and 4-3) and are the same for organic zinc-rich coatings. The major difference is that, with organic zinc-rich coatings, the pigment is zinc dust in high concentrations to attain a dry film pigment volume of 75 percent or greater. This high zinc loading enables the organic zinc-rich coatings to provide galvanic sacrificial protection. The zinc-dust particles within the coating system must be in electrical contact with the thoroughly cleaned, underlying steel surface, and the zinc-dust pigment particles must touch each other for galvanic protection. Usually when formulated into organic vehicles, the binder more thoroughly encapsulates the zinc and reduces the sacrificial capability of the applied film. However, this encapsulation does not prevent galvanic protection by organic zinc-rich primers. In fact, the encapsulation of the organic binder makes organic zinc-rich coatings more tolerant of deficient surface preparation because the binder more readily wets and seals the prepared surfaces where residues of rust or old paint may remain. Also, topcoating with the same generic type of topcoat (e.g., a polyamide epoxy zinc-rich topcoat with a polyamide epoxy topcoat) is more easily accomplished because organic zinc-rich coatings have a less porous surface and are more similar to conventional organic coatings than the inorganic, zinc-rich coatings.

(1) Organic zinc-rich coatings frequently are used to touch up and repair inorganic zinc-rich coatings because the wettability of the organic binder provides better adhesion to

the inorganic surface than another coat of inorganic zinc-rich coating. Organic zinc-rich primers generally are considered to be easier to apply by spray than inorganic zinc-rich coatings, and they are somewhat more tolerant of poor surface preparation because of the wettability and penetrability of the organic binder. Organic zinc-rich coatings have less of a tendency for mud cracking at excessive thicknesses (over 0.13 mm [5 mils]) and are easier to topcoat than inorganic zinc-rich coatings; however, they do not have the heat and abrasion resistance of the inorganic zinc-rich coatings. Organic zinc-rich coatings do not provide the same long-term corrosion protection to steel as most inorganic zinc-rich coatings.

(2) The VOC characteristics of organic zinc-rich coatings are similar to those of the nonzinc-dust-pigmented binders. Organic zinc-rich coatings are highly pigmented, but this does not substantially reduce VOC because the pigment has a high specific gravity and is dense relative to its volume. Generally there is less organic binder per gallon of organic zinc-rich paint, and VOC emissions are slightly less than for nonzinc-rich-pigmented coating systems using the same binder.

(3) Properly applied zinc-rich coatings, zinc galvanized coatings, and thermally sprayed zinc eliminate pitting and under-film corrosion even at voids, pinholes, scratches, and abrasions in the coating system. This cannot be said of any other type of coating, and this protective capability makes zinc coatings unique and widely used. The binders of zinc-rich coatings can be organic or inorganic.

4-10. Volatile Organic Compounds

VOCs are in most protective coatings. Common paint solvents such as aromatic hydrocarbons, aliphatic hydrocarbons, ketones, acetates, and alcohols are photochemically reactive. On evaporation into the atmosphere, these paint solvents react with nitrous oxides (combustion compounds from automotive emissions and burning of fuels) and sunlight to form ozone and air pollutants. In the 1960s, air pollution problems usually were handled by state and local agencies. There was no national goal to address air pollution. In the 1970s, Congress passed the Clean Air Act and established the U.S. Environmental Protection Agency (USEPA). The Clean Air Act gave USEPA the responsibility of identifying the most serious air pollutants and setting national air quality standards for each. Ozone was at the top of the list. The air quality legislation was an attempt to reduce levels of ozone and other air pollutants. Rules limiting the amount of VOCs in paint have been established since then, but they vary from state to state and even regionally within a given state. Such variability in laws regarding VOC emissions has

been of considerable concern to many coating manufacturers whose products are sold nationally. A particular coating material may comply with the laws of one state but not with those of another state. Even within a given state, the coating may be legal in most areas but illegal in certain cities or regions. For years the coatings industry has pushed for national VOC legislation that will supersede and preempt local legislation regarding VOC emissions. However, national VOC legislation has not been enacted, and permissible VOC emissions vary widely, depending on the generic type of coating and the location where it is applied. VOC compliant coatings are formulated principally by increasing the percent volume of solids, chiefly by minimizing solvent content, use of relatively high volume low density pigments, and the use of lesser amounts of stronger solvents. Additionally, the alkyd resin is combined with other synthetic resins (such as epoxies, phenols, and urethanes) and results in a more reactive higher solids coating system. Straight alkyd systems currently are formulated with VOCs of 350 g/L (2.9 lb/gal) or higher. Future formulations probably will require a VOC as low as 250 g/L (2.1 lb/gal). Chapter 11 discusses VOC regulations in detail.

4-11. Powder Coating

Powder coatings are made by mixing resins, pigments, and additives together and heating them to form a melt. The melt is extruded, cooled, and broken up by milling to produce a powder with a particle size distribution of approximately 10 to 100 μm . The article to be coated usually is preheated to 204 to 260 $^{\circ}\text{C}$ (400 to 500 $^{\circ}\text{F}$), depending on the powder to be applied. The pigmented powder is applied, either by immersing the article in a fluidized bed of the powder (which is kept mobile by the passage of air through it) or by electrostatic spray guns. After application, the article being coated is heated to the melting point of the powder so the powder flows together. The powder can be thermoplastic or thermosetting. With thermoset powders, crosslinking agents also are made into a powder, and this powder is applied at the same time as the base powder. After application, crosslinking occurs on melting. Epoxy powder coatings are by far the most popular, although polyester, polyurethane, acrylic, and other resin types can be used.

a. Powder coatings do not readily give satisfactory films at thicknesses below approximately 0.05 mm (2 mils); they require special application and heating equipment. Powder coatings form good-looking, thick, tough coatings that contain no solvent. Because they are VOC compliant, they comprise a technology that is of considerable interest in the protective coatings area. Currently, powders are used mostly in the coating of relatively small items that can be

easily heated to the melting point of the powder being applied. Fusion-bonded powder coatings are applied to preheated pipe surfaces with or without primers. The coating usually is applied 0.30 to 0.63 mm (12 to 25 mils) thick for aboveground pipe installations to eliminate chalking and to maximize surface life; topcoating frequently is done with a urethane coating system.

b. Thermally sprayed organic powders have been applied to structural steel and other large metal objects. The process is expensive and adhesion sometimes is a problem because the large item being coated does not attain a uniformly high substrate temperature when heated; and the applied powder, even though in a liquid "melt," does not have good surface wetting properties. Current furnaces or heating ovens are large enough to handle concrete reinforcing rods, small- to medium-diameter pipe, small structural steel pieces, and sheet piling.

c. Although of considerable interest to the protective coating industry, powder coating has not been used commercially to protect large steel surfaces or heavy, massive structural steel shapes.

4-12. Thermal Spray

a. Thermal spray coatings consist of a process by which an organic powder or metal wire is melted and spray-deposited onto a surface. In the past, metallizing was the term used to describe wire flame spraying. However, because of dramatic improvements in equipment used to heat and spray the molten metal and nonmetallic polymers onto a surface, the term thermal spraying is more descriptive. Thermal spraying is a process by which a finely divided molten metallic or nonmetallic material is sprayed onto a prepared substrate to form a coating. The sprayed material is originally in the form of a wire or powder. The thermal spray-gun heats the wire or powder to a molten or plastic state, and compressed air or gases propel it to the surface being coated and deposit it into a film. Refer to CWGS 05036.

b. Zinc, aluminum, and their alloys are the most widely used metals for thermal spray, corrosion-resistant coatings. These metals provide excellent protection in a variety of marine and industrial environments. After spray application, zinc is anodic to an underlying steel surface. Because of its aluminum oxide coating, aluminum exhibits galvanic protection for only a short period of time. Afterward, the oxidized aluminum coating functions principally as a barrier coat. In general, aluminum corrodes less rapidly than zinc in highly acidic conditions, but zinc performs better in alkaline environments. Zinc frequently is the preferred metal for protection of steel in fresh cold waters, although

aluminum also is suitable. Aluminum is preferable for aqueous solutions above 60 °C (140 °F).

c. Organic sealers or topcoats commonly are used over the thermally sprayed metal to extend the life of the system and provide color for decorative purposes. Common sealers include many of the synthetic resin coating systems, especially vinyls, epoxies, polyurethanes, and phenolics. Sealers are essential for most immersion or severe chemical corrosion applications. Most sealers are applied in at least two coats, the first thinned for penetration into the porosity of the thermally deposited metal coating. The second and sometimes third coat of a sealer are applied unthinned as build coats.

d. Because there are no solvents or volatile material in any metallic thermal spray system, VOC compliance is not a problem. However, VOC compliance may depend on the organic sealer coating used.

e. An advantage of the thermal spray system is that essentially no startup or cleanup procedures are involved. The wire or powder feed stock is fed to the spray gun, the heat source is ignited, and spraying of the molten feed stock begins. On conclusion of thermal spraying, the device is shut off, and the process stops, with virtually no equipment cleanup required.

f. Blast cleaning surface preparation to a clean white metal, preferably with an anchor profile exceeding 0.08 mm (3 mils) is required for any thermal spray coating. Thermal spray metal (and plastic) coatings have little wetting ability at the time of application so cannot penetrate, seal, or encapsulate any contaminants on the surface to be coated. On cooling after application, the metal particles undergo a thermal contraction that applies a shrinkage stress to the metallic film. A minimum anchor pattern of 0.08 mm (3 mils), and preferably 0.10 to 0.13 mm (4 to 5 mils), is required to withstand the shrinkage stresses and to dissipate these stresses over a greater interfacial area between the applied metallic film and the underlying steel substrate.

g. The common methods of thermospray are:

(1) Wire flame spraying. Acetylene or other common fuel gases are combined with oxygen and ignited in the spray gun. A wire—usually zinc, aluminum, or zinc-aluminum alloys but sometimes nickel, stainless steel, or another metal—is fed through the flame, is melted, and is deposited on the surface. Wire flame sprayed coatings generally exhibit lower bond strengths, higher porosity, a narrow working temperature range, and a higher heat transmittance to the substrate than plasma or electric arc spray coatings.

(2) Powder flame spraying. A common fuel gas is used with a metal or plastic powder. The powder is stored in a hopper mounted on top of a spray gun, and a small amount of oxygen is diverted from the gas supply to carry the powder by aspiration into the oxygen-fuel gas flame. The melted powder is carried by the flame to the object being coated. An air/propane mixture is used for polymer powders. The object to be coated must be preheated to at least 79 °C (175 °F) prior to the spray application of the polymer powder. Because of the lower particle velocities obtained, the coatings generally have a lower bond strength, a higher porosity, and a lower overall cohesive strength than the coatings produced by any of the other thermal spray methods. The bond strength and other film properties can be improved considerably by preheating the substrate to 49 °C (120 °F) or more prior to application of the powder.

(3) Electric arc spraying. The spray gun used in electric arc spraying uses two feed stock wires as electrodes. An electric current is applied across the wires so that an electric arc is formed at the intersection. Heat from the electric arc melts the wires, a stream of compressed air flows across the arc zone, and the melted metal is removed from the wires and propelled to the surface. Because of the high temperatures in the arc zone, the coatings have excellent adhesion and high cohesive strength. Super heating of the particles after impact may lead to a metallurgical "weld" bond with some metals, substantially increasing adhesion and cohesive strength.

(4) Plasma spraying. Plasma is a hot gas issuing from the spray gun; it resembles a bright flame and is created by passing inert gas through an electric arc within the gun. The arc heats the gas to temperatures well above the melting point of any known substance. Powder feed stock is introduced into and melted by the plasma stream that also carries the molten metal to the work piece. The plasma system produces excellent quality coatings, but the equipment is complex, expensive, and difficult to operate. Plasma spraying is used when coatings are needed to provide the utmost in corrosion protection against chemical or high temperature corrosion, and when the work can be done in a shop environment.

4-13. Galvanizing

a. Hot dip galvanizing is the process by which a zinc protective coating is applied to steel by immersing an object in a molten zinc bath. Prior to immersion in the zinc bath, contaminants on the steel must be removed. Oil, grease, and other surface deposits are removed by immersing in a hot water detergent solution prior to pickling, steam cleaning, or steam-detergent cleaning the steel. The steel surface also must be thoroughly cleaned of mill scale and

rust. This is usually done by sulfuric acid or phosphoric acid pickling. The steel to be galvanized is immersed in a hot acid bath. The hot acid aggressively attacks the steel surface, cleaning, etching, and roughening it. After continuous strip or batch pickling, the steel is water-rinsed or dipped to remove acid residues prior to immersion in the molten zinc galvanizing bath. The immersion in molten zinc may be done by one of two methods: continuous or batch processing. Sheet steel may be hot dipped by continuously passing the metal through a molten zinc bath. Continuous processing is highly automated and often is associated with steel mill operations. Batch processing generally is performed on fabricated items that range in size from large structural steel objects to small items such as nuts, bolts, and fasteners. With batch galvanizing, the objects are submerged into the molten zinc bath, held there for a suitable time, then removed.

b. A major advantage of galvanizing is that the zinc coating alloys itself with the steel. The extent of the alloy is a function of the heat of the zinc bath (the bath is generally maintained at a range of 443 to 460 °C [830 to 860 °F]) and the amount of time the steel is submerged in the bath. The greater the submersion time, the greater the extent of the iron-zinc alloying. The item being galvanized must be at the bath temperature for optimum galvanizing adhesion. This, however, has two disadvantages. The object being coated must not undergo any undesirable property changes at the temperature required for galvanizing. Also enclosed or sealed cavities in the object being galvanized (particularly with hot dip batch galvanizing) must be avoided by design or be opened by drilling to provide a vent hole to allow release of entrapped air that will expand when heated in a galvanizing bath.

c. Corrosion protection afforded steel by galvanizing is greater than that provided by thermal spraying zinc-rich or organic coatings of similar thicknesses. This is a result of the smooth, continuous nature of the zinc coating deposited during the hot dip process and the iron-zinc alloying that occurs at the interface between the zinc coating and the steel surface. For small steel objects, grating, small-diameter piping, conduit, and other configurations with a high surface area-to-weight ratio, galvanizing is preferable to painting and thermal spraying because immersion in a molten zinc bath readily coats all surface areas quickly and economically. Conversely, when coating thick, heavy steel objects with a relatively low surface area-to-weight ratio, thermal spraying and/or painting may be more economical.

d. Although almost any steel can be galvanized, steel chemistry can dramatically affect the thickness, structure, and appearance of the galvanized coating. Silicon, phosphorus, carbon, and manganese may be present in steel

and affect the galvanizing properties. The most influential steel constituent affecting galvanizing is silicon, which is added to steel as ferro-silicon to remove oxygen from the molten steel before casting. In high silicon steels, an undesirable increase in coating thickness occurs because of the accelerated growth of the zinc-iron alloyed layers. This growth is caused by the formation of loosely packed small grains or crystals in the outermost alloy layer of the coating that allows zinc from the bath to penetrate to the steel surface. In general, steels with the following maximum impurity levels are best suited to galvanizing: 0.05 percent silicon, 0.05 percent phosphorus, 0.25 percent carbon, and 1.3 percent manganese.

e. Hot dip galvanizing has a number of advantages, including the ability to coat recessed or difficult-to-coat areas (such as corners and edges) with a sufficient coating thickness. Also because the coating is metallic and metallurgically combined with the steel, it has good abrasion and corrosion resistance. When coating steel with a large surface area-to-weight ratio, galvanizing is much more economical than painting because galvanizers charge by the weight of the object being galvanized and painters charge by the square foot of surface area of the object being painted. A major disadvantage is that the hot dip process is not portable, and the object being coated must be taken to the zinc-coating facility for galvanizing.

f. Hot dip galvanizing causes no significant alteration in the bend, tensile, and impact properties of galvanized steel, so steel strength and ductility are unaffected. Welded structures have higher strength when galvanized than when uncoated because hot dip galvanizing reduces weld stresses by 50 to 60 percent. For most steels, little reduction in fatigue strength occurs as a result of galvanizing. Steel does not embrittle as a result of hot dip galvanizing. Hydrogen embrittlement does not occur when ordinary carbon or low alloy steels are galvanized. Hardened steels may become embrittled if the hydrogen picked up during the pickling cleaning operation is not expelled during immersion in the molten zinc bath. Steels of medium to high strengths that have been severely cold worked may have local areas susceptible to hydrogen embrittlement. As a rule, however, hydrogen embrittlement as a result of cold working is not a problem for steel subject to hot dip galvanizing.

g. Coatings can be successfully painted immediately after galvanizing or after extended weathering. A white rust-preventative oil or wax may be applied to the galvanized surface to prevent the formation of zinc-corrosion products such as zinc hydroxides, oxides, and carbonates that result in a white discoloration on the galvanized surface. If painting is to be done immediately after galvanizing, check to ensure that a rust preventative

has not been added. The freshly galvanized surface should be roughened slightly by light brush blast cleaning or mechanical means. Alternatively, vinyl butyral wash primers or other pretreatment primers can be applied that will etch and adhere to the underlying galvanized surface.

h. If coating after weathering, the galvanized surface will be eroded by zinc corrosion and the formation of insoluble zinc-corrosion products. The zinc corrosion roughens the galvanized surface and frequently no further mechanical roughening or brush blast cleaning is required. However, care should be taken to ensure that all loose zinc-corrosion products are removed by scrubbing or power washing the surface prior to painting. Wash primers, or primers specially formulated for application over galvanized surfaces, frequently are preferred.

i. Galvanized steel can be topcoated with any nonsaponifiable alkali-resistant paint. Zinc dust, zinc oxide-containing paints are particularly recommended, as are zinc-rich coatings. Water-based acrylic latex emulsions, epoxies, vinyl copolymer paints, and chlorinated rubber and coal tar epoxy coatings all have been applied with good success over properly prepared galvanized steel surfaces.

4-14. Tapes and Wraps

a. Protective tapes and wraps are used almost exclusively for protecting pipelines and tubular structural shapes from below-grade or (underground) corrosion. Cathodic protection is used in many situations to supplement corrosion protection. The tape or wrap must provide a barrier resistance to the below-grade environment, have good adhesion, and be able to act as an effective electrical insulator to aid in effective cathodic protection.

b. A tape is a composite material consisting of at least two layers. The first or innermost layer is usually a soft, elastomeric material formulated to adhere to an underlying substrate. The substrate can be either primed bare metal or another tape layer. The tape backing or outer layer is a monolithic polymeric material designed for tensile strength, mechanical strength, temperature, and electrical resistance. Typical tape backings include polyvinylchloride, polyethylene, polyolefin, butyl, ethylene propylene diamine monomer (EPDM), and, occasionally, nylon or glass fibers. Adhesives are usually butyl rubbers or butyl chlorinated rubbers but can be petrolatum and petrolatum wax compounds.

c. The tapes can be cold applied, hot applied, and cold applied with subsequent heat application as a heat-shrink material. Multilayered tapes frequently are used on a pipeline by applying a one-tape system then overcoating it

with a different tape system. When this is done, the inner layer is designed primarily for corrosion protection, and the outer layer is designed to resist moisture, soil stresses, UV light, or other environmental influences.

d. Most tape systems are applied over a blast-cleaned surface, usually SSPC-SP 6 or better. This standard generally is a requirement for all adhesives except those based on petrolatum wax, which can be applied over a lesser prepared surface because of its wettability and softness. Most tapes perform better when applied over a primer, which commonly is an epoxy. The primer provides a bonding surface for best adhesion of the subsequently applied tape coatings.

e. Tape systems are applied by hand or, preferably, by a hand-assisted tape wrapster that is pushed and pulled around a pipe by as many as four or five workers per machine. Powered wrapsters provide the best application and allow for a more constant tension, uniform overlaps, fewer wrinkles, and a lesser clearance underneath the pipe (as little as 304.8 mm [12 in.]). Tape wrapping machines are available that will simultaneously apply two tape layers to a pipe. These tape wrapping machines are most useful for over-the-ditch applications.

f. For tape applications in the pipe mill or fabricating shop, surface preparation by blast cleaning is the most common, usually to an SSPC-SP 10 quality. Application of a primer and two or more tape layers applied by automatic pipe-coating equipment under constant tension of 10 to 14 psi results in a tight, wrinkle-free coating. The coating is inspected by automated high voltage holiday inspection (minimum 6,000 V). After mill application of a tape system, careful handling is required to avoid damaging or stripping the applied tape system.

g. In the pipe mill, hot-applied plastic tapes also have been used. The pipe surface is cleaned to an SSPC-SP 10 and heated to approximately 121 °C (250 °F) to melt the tape adhesive to provide a good bond. Mill-applied tape coating systems require careful handling and installation, and over-the-ditch application eliminates the need to repair shipping and handling damage. However, over-the-ditch application generally is more labor intensive and is subject to weather variables and adverse application conditions. During installation of any pipeline system—whether coated by a tape wrapping system, fusion bonded system, or extruded high density polyethylene wraps—care is necessary during backfilling operations to prevent rock and stone damage and impact into the coating. Insulating mats and/or blankets are sometimes wrapped around a pipe to prevent backfilling damage or, alternatively, specially conductive backfilling earths are initially placed around the pipe layer

prior to filling the ditch. Another tape system, extruded polyethylene, is relatively new and is gaining acceptance in the United States. This coating system generally consists of blast cleaning to SSPC-SP 6 followed by the application of an epoxy primer to approximately 0.05 mm (2 mils) dry film thickness. The pipe then is heated to approximately 135 °C (275 °F) and approximately 0.20 mm (8 mils) of a polyethylene copolymer adhesive is extruded around the pipe, followed by 3 mm (118 mils) of a polyethylene outer wrap extruded spirally over the adhesive. The preheating melts the adhesive and provides wetting capability. Additionally, the polyethylene extrusion to the hot pipe shrinks to form a tightly adhered, thick, seamless coating with high resistance to mechanical damage, moisture permeation, and UV light.

h. During pipe-laying operations in the field, the joints must be protected by application of paints or protective coatings or, more commonly, a tape wrapping system.

(1) Polyvinyl chloride tapes. Tapes with a PVC backing can be used with a variety of adhesive materials, including butyl rubber and petrolatum wax. The greatest advantage of PVC-backed tapes is that they have an ability to conform to regular substrates and provide a good barrier to penetrating moisture. However, because of plasticides and migration, sometimes the backing material separates from the adhesion. PVC backings are suitable for temperatures up to 60 °C (140 °F).

(2) Polyethylene tapes. Polyethylene-backed tapes most commonly are used with butyl or chlorinated rubber adhesives. These tapes are used as outer tapes to provide increased mechanical strength and UV light resistance. They can be used over primed steel as an inner tape wrap because of their excellent adhesive quality. Polyethylene tapes are considered suitable for use in cold climates because they retain their flexibility at temperatures as low as -40 °C (-40 °F). The polyethylene backing generally ranges from 0.25 to 1.27 mm (10 to 50 mils) thick; adhesive ranges from 0.08 to 0.30 mm (3 to 12 mils) thick.

(3) Petrolatum tapes.

(a) Petrolatum wax, obtained from the refining of petroleum, is purified and used as a corrosion-protective material. The petrolatum is a soft, viscous to semisolid waxy-like material with excellent wetting properties. Petrolatum tapes are fabricated by impregnating the petrolatum into a woven or nonwoven, cellulose-free synthetic fiber fabric, usually nylon or glass fiber. Inert fillers are added to improve thixotropy. The resulting coating possesses a low water vapor transmission rate, is relatively moisture impermeable, and is nondrying,

nonhardening, nonhazardous, and nontoxic.

(b) Petrolatum tapes have some moisture-displacing capability and often are applied over hand- or power tool-cleaned surfaces (instead of blast-cleaned surfaces as required by most other tapes). Because of the high conformability of petrolatum tapes, they are suitable for use over irregular surfaces, on pipelines, and to protect valves, flanges, and other irregular shapes. Petrolatum tapes are soft and they are susceptible to mechanical damage. A polyvinyl chloride outer wrap or membrane is applied over the petrolatum tape to improve mechanical properties, particularly during handling and backfilling. This exterior wrap also keeps the petrolatum from oxidizing and drying out.

(c) Petrolatum formulations have been developed to allow use at temperatures as high as 82 °C (180 °F). These tapes are well suited for protecting metal couplings and valves and other pipeline irregularities and for coating repairs on existing pipes when the existing coating has deteriorated or failed in service.

(4) Coal-tar and asphalt tapes. Coal-tar and asphalt mastic tapes are used as hot-applied systems. The backing is usually a synthetic fiber of nylon or woven glass fiber. These tapes have good resistance to water penetration and, when properly applied, have excellent adhesion. They usually are used for over-the-ditch application and for the protection of welded joints.

(5) Butyl or EPDM vulcanized rubber tapes. Butyl or EPDM vulcanized rubber-backed tapes have excellent flexibility, mechanical resistance, and moisture resistance.

The adhesive of these tapes is usually a butyl or chlorinated rubber, and this type of tape is noted for good adhesion and resistance to mechanical damage.

(6) Heat shrink polyolefin tapes. A crosslinked polyolefin backing is combined with a high shear strength crystalline adhesive to form a heat shrinkable pipeline tape. Prior to tape wrapping, the steel is usually hand- or power tool-cleaned and preheated to approximately 60 °C (140 °F). The tape is wrapped around a pipe with a 50 percent overlap and heated with a propane torch after wrapping. Heat from the torch causes the crystalline adhesive to melt and flow, filling surface irregularities. Additionally, the backing shrinks tightly to the steel substrate to provide good adhesion and conformability. There are calorimetric heating indicators in the backing to indicate when the proper temperature has been reached.

4-15. Other Coatings

Any listing of coating systems cannot be all-inclusive. There always will be specialized coating systems that are not widely used or are of little interest to USACE. Some of these systems may include fluoropolymer coating systems, used principally for high heat, corrosion-resistant surfaces; silicone resin coating systems, used as thin film, high heat systems or in combination with metal or ceramic frits for high heat, abrasion-resistant corrosion service; chlorinated rubber, neoprene, and other coating systems that are not widely manufactured and have been replaced by other generic-type coating systems; and variations or combinations of systems that are not different enough to warrant a separate category.

Chapter 5 Coating System Selection

5-1. Introduction

a. A systematic approach to coating selection for new construction and maintenance painting is described in this chapter. The first section details the criteria for selecting a coating system based on the service environment(s), surface preparation requirements, and options for coating application. Other considerations such as VOC concerns, coating cost, supplier recommendations, ease of application, and maintainability are discussed.

b. After a coating system is selected, alternative methods of surface preparation and application are explored. Special sections are devoted to the advantages/disadvantages of shop versus field cleaning/painting, difficult to coat areas, and the use of cathodic protection alternatives in those areas. The balance of this chapter is devoted to reviewing existing systems, candidate maintenance, and new coating systems options for given USACE structures service environments. Also, special concerns or cautions associated with these coating system choices are discussed.

5-2. Criteria for Selecting a Coating System

No single coating or coating system can satisfy every service condition or environment that may be encountered in a given civil works facility. Selecting candidate coating systems for an exposure environment depends on identifying and understanding how each of the environments impact various coatings. For example, chlorinated rubber or vinyl coatings, which are thermoplastics, would not be used in locations subjected to high heat or strong solvents because they would quickly dissolve or soften. If alkyd enamels were used in an environment with, for example, caustic conditions, they would soften, swell, and quickly disbond as a result of saponification. Chemistry, experience, and the coating system performance history have illustrated these facts. The Paint Systems and Painting Schedule section of CWGS 09940 and the Supplementary Application Instructions contained therein show paint systems that will provide satisfactory, cost-effective performance based on given service environments. Characteristics of the environment that the coating system will encounter must be well identified. Once the environmental exposure has been properly determined, the process to select coatings systems that have a known history and track record of successful use in these identified environments may begin.

a. *Identifying the service environment(s).* Exposure environments that have the greatest impact on coatings and

coating systems performance will be described briefly here. Picking the correct coating for painting projects might be described as a process of elimination rather than one of selection. Probably the most important step in coating selection is to evaluate the conditions under which the coating must perform. This cannot be a superficial evaluation but must consider all the conditions that may exist. Even small and seemingly irrelevant factors may affect coating system performance. In most situations, a combination of two or more service environments act together to create a hostile environment. Chapter 4 provides detailed information on the environmental resistance qualities of various generic coating types and should prove valuable when used in conjunction with this chapter.

(1) Temperature extremes. Most applied coating systems are subject to temperature variances within their applied environments. For the most part, these fluctuations are moderate (normal atmosphere fluctuations). Even normal atmospheric temperature variations have an effect on coating performance (i.e., piling studies performed by USACE show a significantly higher rate of coating failure on pilings off the coast of South Florida than in the Cape Cod area. Additionally, in many instances, unique processes or system operations may generate adverse (cold or hot) temperatures outside the normal. Extreme cold or heat can cause brittleness, poor impact resistance, shrinkage, or loss of adhesion and may alter the corrosion-prevention characteristics of the coating system. High temperatures also tend to aggravate the corrosivity of the environment severely (i.e., many acids become increasingly aggressive with temperature increases). Curing mechanisms involved with conventional coatings frequently are temperature dependent. With high heat, the curing process may occur too rapidly or, conversely, in cold temperatures curing may not occur at all. Coatings to be applied in extremely cold environments must have excellent adhesion, resiliency, and plasticity. Likely candidates for heat-resistant coatings are those modified with silicone and/or metal flake (i.e., aluminum, stainless steel). Some inorganic, zinc-rich coatings can be applied at temperatures as cold as -18 °C (0 °F) and provide excellent corrosion protection in the extreme cold.

(2) High humidity. High humidity frequently is accompanied by condensation. Consequently, such a continuously wet, heavily moisture laden environment is often considered to be in a state of constant immersion. A water molecule is extremely small and can pass through the molecular network of even the most moisture-resistant protective films. Each coating and resin type has a unique moisture vapor transfer rate. Obvious coatings for such continuously moist environments should exhibit low moisture vapor permeability (MVP) and water absorption

rates. Industry practice generally has found that, the lower the moisture vapor transfer rate, the better corrosion protection the coating provides. Commonly used coatings with typically low moisture vapor transfer rates are formulations of two-part epoxies, vinyls, coal tars, and respective modifications of these coatings. Coatings pigmented with metallic or glass flake have been found to improve moisture resistance and lower the MVP rate of some coatings.

(3) Immersion. Immersion service coatings are exposed to water solutions ranging from highly pure deionized water to water containing high concentrations of various chemicals, acids, or alkali solutions. Specific immersion linings may be subject to the effects of storage of petroleum or solvents. Primarily though, water is the main exposure element in immersions. Coatings for immersion service must exhibit good adhesion, moisture resistance, vapor transfer, ionic penetration, cathodic disbondment, osmosis, and variances in temperature. Examples of coatings that traditionally have performed well in immersion are: coal tar epoxies (CTE), vinyls, untopcoated zinc-rich coatings, and modifications of epoxy coatings.

(4) Oxidizing-reduction. Oxidizing environments—such as atmospheric service or areas of ozone generation and strong oxidizing agents such as bleach or nitric acid—are more common than reduction environments. Most coatings are more susceptible to oxidation than to reduction. Oxidation may cause coating film brittleness and loss of cohesive strength; a common example of this is an old, weathered alkyd that can oxidize to an almost powdery state after many years. Generic coating types that historically have performed well in oxidizing environments are: CTEs, chlorinated rubber, and formulations of epoxies and polyurethanes.

(5) Extreme pH. Extremes of pH, such as strong acid or alkaline environments, can have a dramatic effect on coatings systems selection. The degree of impermeability of the chosen coating to the environment is of primary importance. The coating film essentially must be inert to prevent a reaction with the environment or permeation of the solution into the coating film. Alkali resistance is vitally important to a primer coating. Chemical reactions that take place in the corrosion process produce strong alkaline products that are deposited on the substrate. Subsequently, any primer that is not resistant to these by-products will have a tendency to fail because of cathodic disbondment. This failure can result in additional undercutting of the coating and the spreading of underfilm corrosion. Substrates such as concrete typically have a high alkalinity; therefore, a coating system chosen for a concrete substrate also must exhibit good alkaline resistance. Formulations of coatings that have a good history of performance in extreme

pH environments are vinyls, chlorinated rubbers, and epoxy modifications. However, alkyd or oil-containing coatings tend to have a poor resistance to alkalinity and should not be used in such an environment.

(6) Solvent exposure. The function of solvents in coating formulation in relation to the application properties of the coating is well known. However, solvents often become an exposure environment to the dry-cured coating system. The effects of the solvent on the coating system generally will vary by solvent type and the resistance of the generic type of coating that has been applied. There are numerous types of solvents. Typical solvents frequently can be classified into two categories: hydrocarbons and oxygenated solvents. A less important group of solvents are called the terpenes. Hydrocarbons are so named because their molecules contain only hydrogen and carbon atoms. The molecules of oxygenated solvents also contain oxygen atoms. But some commonly used oxygenated solvents may contain atoms of other chemical elements such as nitrogen. Hydrocarbon solvents more commonly are found than oxygenated solvents. Oxygenated solvents and hydrocarbon solvents frequently are blended for use in lacquers, catalyzed coatings, and synthetic resins solutions. As with many other exposures, a high degree of impermeability is necessary for the coatings to resist solvents. The coating system chosen must not be dissolved or softened by the solvent in the exposure environment. For example, USACE vinyl systems are resistant to solvents of the aliphatic variety and most often can tolerate spills from aromatic hydrocarbons. However, the stronger oxygenated solvents will readily attack, soften, and dissolve the vinyl film. Therefore, it is necessary to make a good system selection because the binder may be dissolved easily and softened by various levels of solvency strength. Historically, two-component highly crosslinked coatings, such as formulations of epoxy and urethane coatings, have exhibited good solvent resistance. Therefore, the blend and type of solvent in the exposure environment should be identified so the appropriate coating system can be chosen. When all pertinent factors have been identified, coating manufacturers can be consulted for system recommendations. The major manufacturers of high performance protective coatings have an excellent understanding of the temperature and chemical exposure limitations of their products. In fact, many publish tables of chemical resistance for various coatings and include some of this information in technical product data sheets. Specific facility coatings histories, manufacturers' performance history, and published coating system service life data are particularly helpful. When searching for such information, the exposure environment must be accurately assessed to select only those coating systems with a high probability of success and/or a proven track record. When a process is new and the exposure environment is uncertain, field test patches of candidate products can be applied in

that environment and evaluated. If a new environment can be identified and simulated, screening and testing of candidate materials can be performed by qualified laboratories using specially designed test apparatus. However, the key to success for any situation rests with thorough, accurate identification of the exposure environment.

(a) Hydrocarbons. There are two types of hydrocarbon solvents: aliphatic and aromatic. Special blends of these solvents have been developed to form solvents called semi-aromatics. Aliphatic and aromatic hydrocarbons differ in the way in which the carbon atoms are connected in the molecule. This characteristic structural difference leads to a sharp difference in the chemical and toxicological properties. The aromatic hydrocarbons are the stronger solvents for coating film formers. They also are more irritating to humans in both liquid and vapor forms. Typical aromatic hydrocarbons are: benzene, toluene, and xylene. Typical aliphatic hydrocarbons are: hexane, heptane, and odorless mineral spirits. Ordinary mineral spirits are mostly aliphatic hydrocarbons. Aromatic and aliphatic hydrocarbons generally are derived from heat distillation of petroleum products. They generally are found as a blend of aliphatic and aromatic components and are readily available in an extensive range of solvent strengths and evaporation rates.

(b) Oxygenated solvents. Oxygenated solvents are manufactured by a variety of processes. Those most commonly known of these solvents are: alcohols, ethers, ketones, and glycol-ethers. Typically, there may be a blend or combination of these solvents in the exposure environment. Examples of alcohol solvents are: methanol, ethanol, isopropanol, and butanol. Examples of ether solvents are: ethyl acetate, isopropyl acetate, butyl acetate, and butyl cellulosolve acetate. Examples of ketones are: acetone, methyl ethyl chloride, methyl isobutyl ketone, and cyclohexanone. Examples of glycol-ethers are: cellulosolve and butyl cellulosolve.

(c) Terpene solvents. These solvents are derived from the sap of pine trees; examples are terpene, dipentent, and pine oil.

(7) Wet/dry cycling. Alternate wet and dry cycling, such as that associated with atmosphere and weather, may have a significant effect on the performance of a coating system. Coating subject to wet and dry cycling must exhibit strong adhesion, low moisture vapor transfer rates, and good corrosion and undercutting resistance. Although a significant number of coatings will perform satisfactorily in a cycling environment, coating system selection mainly will depend on other in-service elements that impact this environment.

(8) Thermal cycling. Thermal cycling naturally generates the forces of expansion and contraction. For a coating system to provide maximum protection to the substrate, it must have the ability to expand and contract with the substrate. For the most part, thermal cycling is associated with normal atmospheric weathering. For example, a metallic substrate may heat up rapidly when exposed to the sunlight; however, when the sun sets or if it becomes cloudy, the temperature can rapidly decrease. Such stresses must be withstood by the coating system without loss of adhesion or checking and cracking. Acrylics, vinyls, and inorganic zinc coatings have proven exceptionally resistant to fluctuations in temperature.

(9) Ultraviolet exposure. Resistance to ultraviolet (UV) radiation is extremely important. Sunlight can rapidly degrade a coating and will cause a complete loss of film integrity, resulting in chalking, loss of gloss, fading, and brittleness in a rather short period of time. Such degradation may result in an aesthetically unacceptable coating appearance. Specific generic coating types exhibit better resistance to UV light than others. For example, a two-component epoxy coating will chalk rather rapidly under exposure to UV light, but formulations of acrylic aliphatic polyurethanes remain stable on UV light exposure. Inherent in most alkyd and oil-based products is poor resistance to UV exposure, which results in chalking, loss of gloss, and loss of color. However, modifications with silicone (i.e., silicone alkyds) can greatly enhance the performance characteristics of surfaces exposed to UV light. Modifying alkyds with silicone combines the workability of the alkyds with the durability, gloss retention, general weather resistance, and heat resistance of the silicones. Silicone alkyds are widely used as a maintenance upgrade finish over conventional alkyd coatings because of these improved properties. Silicone alkyds are used rather extensively for stack coatings and similar areas where moderately high temperatures are involved. USACE structures at which alkyds are used and improved gloss retention, weather resistance, and durability are desired should be considered for upgrades with silicone alkyd products.

(10) Impact/abrasion. Impact and abrasion resistance are extremely important characteristics in coating selection. Although impact and abrasion resistance frequently are discussed in the same breath, they can designate two different exposure environments. For example, a coating must resist rupturing from the rapid expansion of a metal as it is deformed from a sudden impact. To resist this type of impact, coatings must have a high degree of flexibility such as most formulations of a vinyl coating. Formulations of epoxies and polyurethane coatings are excellent choices for abrasion resistance, but the inherent brittle qualities of the

coating would cause it to fracture easily on impact. These coatings perform best where abrasion may be in the form of heavy equipment movement, foot traffic, or even scouring by tools and equipment. Abrasion also may be a result of naturally occurring phenomena, such as windblown sand or sand carried by waves of water. Consequently, it is extremely important for the coating specifier to determine if the exposure environment necessitates a coating that will withstand constant abrasion, sudden impact, or a combination of the two.

(11) Special exposures. Special exposure environments such as food processing and potable water may be subject to regulations of the Food and Drug Administration (FDA) and the National Sanitation Foundation (NSF). In addition to mixed exposure conditions, there most certainly will be extraneous circumstances such as inaccessibility and limitations on surface preparation methods. These situations could have a significant effect on coating system selection and should be thoroughly investigated prior to choosing a coating system. Sources of help for making decisions about these situations are discussed in the ensuing paragraph.

b. Identifying areas that cannot be properly coated.

(1) Many times due to design or configuration, structures, items, or areas to be coated do not readily lend themselves to proper surface preparation and coating application. This is particularly true with items designed with back-to-back angles or cavities and crevices that can result from riveted or bolted connections, weld undercutting, overlapping plates, skip welds, lap welds, etc. Essentially, any area that provides cavities or crevices in which air, moisture, dirt, or debris can become entrapped is a candidate for premature coating failure, unless properly sealed and/or caulked. Some initial design considerations such as full seal welding or alternative construction materials (i.e., fiberglass) could be used to avoid such problem areas. However, most structures are already built, and it would not be cost effective or practical to institute design changes. Consequently, caulks and sealants are widely used in many areas. For example, caulking compounds perform well when immersed in fuel oils, water, and chemicals. However, caution should be used when selecting caulks and sealants for immersion environments. Previous successful use in a given immersion environment should be an essential selection factor. Coating suppliers and manufacturers can be a good source of information about whether a particular caulk or sealant will provide good protection in atmospheric or immersion service environments.

(2) Recently, technological developments in the use of low viscosity, penetrating epoxy sealers make them practical for use in areas that are difficult to coat. These two-

component products are tolerant of poor surface preparation, produce minimal stress in the curing process, and are 100 percent solids. These products work with wicklike action, which penetrates and effectively seals off the hard to reach areas; and they can be applied by flooding the surface (with a garden-type low pressure sprayer), much like using a penetrating oil, and allowing the epoxy product to "wick in" and seal back-to-back angles and cavities. Products such as these are proving to be viable alternatives in lieu of, or in conjunction with, caulking compounds in atmospheric exposure.

c. Identifying regulated requirements. In addition to performance restrictions on coating types in various service environments, there are regulations on the type and amount of VOCs that can be emitted into the atmosphere. These regulations vary from state to state and even from county to county. Compliant coatings are being formulated with a higher solids content, less solvent, and with water as the solvent. Prior to specifying a coating, it is important to investigate national, state, local, and corporate regulations regarding the use of non-VOC-compliant coatings. The Clean Air Act and the Clean Air Act Amendments of 1990 are affecting the coatings industry by requiring the U.S. Environmental Protection Agency (USEPA) to restrict emissions of VOCs into the atmosphere. (Chapters 4 and 11 provide additional information.)

(1) Because of the emissions from coatings (solvents in particular can contribute to the formulation of ozone at low atmospheres), the USEPA has been directing the use of VOCs. Nationwide regulations are being developed to restrict the VOC content in architectural and industrial maintenance coatings for field applications. These restrictions list the maximum VOC per gallon of paint, and they vary according to the category of coating and its usage.

(2) Before specifying coatings for marine, architectural, or industrial use, the state and local bureaus of air pollution control should be contacted to determine the specific restrictions that may apply. Regulations may specify the maximum allowable VOC per gallon or the total number of gallons permitted to be applied per day or year. After the limitations are determined, the coating manufacturers can be consulted to determine the specific brands that are suitable for use. Note that when investigating acceptable coatings, it is the VOC "as applied" that counts rather than the VOC "in the can." For example, a solvent-based coating containing 419 g/L (3.5 lb/gal) VOC in the can that must be thinned 10 percent for application will exceed the 419 g/L (3.5 lb/gal) threshold at the time of application. If the local regulations restrict the use of materials to those containing 419 g/L (3.5 lb/gal), this coating could not be used.

d. *Identifying surface preparation alternatives for new construction.* Coating selection is influenced by the degree of surface preparation that can be achieved as well as by the method of coating application that may be allowed. Surface preparation usually is determined by the severity of the service environment (i.e., immersion, normal weathering, dry interior), the type of substrate, and the coating system. As a general rule, the more aggressive the environment is surrounding the item to be coated, the higher the degree of cleaning required. Cleanliness has a direct influence on adhesion and long-term service life. For example, in immersion service, a minimum acceptable surface cleanliness is generally in conformance with SSPC-SP 10, although SSPC-SP 5 is preferred. Cleanliness is only one factor in surface preparation. Profile or surface roughness also is a factor. A rule of thumb for profile or anchor pattern is that the depth of profile should be from one fourth to one third of the total coating thickness, up to a thickness of 0.30 mm (12 mils). For example, a coating system of 0.30 mm (12 mils) should be applied over a profile of from 0.07 to 0.10 mm (3 to 4 mils). The purpose of the profile is to allow for mechanical bonding of the coating to the surface. Profile actually increases the total amount of surface area wetted by the coating system. In new construction, there generally are few logistical limitations of blast cleaning, if the substrate is to be shop-prepared. However, because of the proximity to sensitive areas in the field, abrasive blast cleaning may not be allowed. The relative advantages and disadvantages of each procedure are discussed below. (See Chapter 7 for additional details on surface preparation.)

(1) Total field blast cleaning and painting of new steel. Blast cleaning and painting of new steel may be performed entirely in the field after erection, or they may be accomplished entirely in the shop. The primary advantage to total field blast cleaning and painting is that damage to the paint system prior to service is essentially eliminated. Total shop-applied systems may be damaged by handling and the installation/erection process or onsite repair procedures. Uncontrollable variables, such as weather and climate, often adversely affect field operations and eventually shop allocation if the shop is poorly equipped.

(a) Neither field blast cleaning nor painting may be performed during high humidity, rain, fog, haze, etc. Typically, paint specifications prohibit any work when the surface temperature of the steel is less than -15 °C (5 °F) above the dew point. The influence of the dew point is more of a concern on coastal sites or in the cooler northwest and northeast sections of the country. If work is performed when the dew point is too high, the consequence may be flash rusting of the freshly cleaned steel, moisture entrapment between the paint and the substrate causing poor

adhesion, or moisture mixing with the freshly applied paint inhibiting proper curing. Conversely, extremely dry, arid conditions can present problems if the coating specified requires a certain amount of moisture in the air to properly cure (i.e., moisture cured urethanes and ethyl silicate type inorganic zinc-rich primers).

(b) Wind also may interfere with the field work by causing clouds of blast cleaning waste and overspray to drift onto the roadways, neighborhoods, and rivers. The liabilities incurred from drift on automobiles or into nearby residential neighborhoods may be substantial. Many specifications prohibit spray painting where wind speeds exceed a certain level or blow in a specific direction. Furthermore, on some days the wind is too strong to work from staging for safety reasons. Paint application by brush or roller can prevent drift; but it is slower, more labor intensive, and more expensive. In addition, not all paints readily lend themselves to application by brush or roller. This is especially true of some formulations of the high performance coatings such as vinyls, inorganic zinc-rich, acrylic urethanes, and other high-build high solids coatings.

(c) Temperature is another factor that may interfere with field work. The temperature of the steel after overnight cooling is less likely to be at least -15 °C (5 °F) above the dew point. Many paints, especially epoxies, cannot be applied when the steel temperature is below 10 °C (50 °F), because the curing process is temperature dependent. Few paints can be safely applied at or near 0 °C (32 °F). Because low temperatures restrict coating application, it is impossible to blast clean or paint for months at a time in the northern areas where winters are severe. High temperatures, above 32 °C (90 °F), also can present problems by reducing coatings pot life or by causing solvents to flash off too rapidly. This results in incomplete film formation, poor wetting, dry spray, loss of gloss, and poor adhesion to the substrate because of poor wetting. Also, topcoats applied over inorganic zinc primers are more likely to bubble and pinhole at high temperatures.

(d) To blast clean and paint a structure in the field, the erection of extensive scaffolds and staging may be required. Staging may be an additional expense, and a subcontractor may be needed to erect the staging and coordinate scheduling arrangements. Staging may have to be moved a number of times before the job is completed. Blast cleaners and coating applicators have limited mobility and accessibility when work is done from staging or scaffolds. Such limitations decrease the amount of work performed and the production quality. Limited accessibility hampers the applicator as well as the inspector.

(e) There is a greater opportunity for surface

contamination when all of the blast cleaning and coating are performed in the field. Uncoated beams generally receive less care and may be dragged across the ground and/or be subjected to dirt or road salts in transit, and the beams may be exposed to coastal or industrial atmospheres at the jobsite. Contamination may occur on the steel or in between field-applied coats of paint. Steel contaminated with corrosive salts or anions is difficult, if not impossible, to thoroughly clean later.

(f) Health and environmental considerations related to blast cleaning in the field also must be evaluated. Current Occupational Safety and Health Administration (OSHA) guidelines require the contractor to take precaution to protect workers from exposure to free silica and nuisance dust during blast-cleaning operations. (See Chapters 10 and 11 for detailed information on these subjects.)

(2) Total shop cleaning and painting. Greater control over the working environment and easy accessibility to the entire surface are the principal advantages to performing work in the steel fabrication shop. Accessibility to all areas of the structural steel is greatly improved in the fabrication shop. The use of overhead cranes to manipulate pieces of steel reduces manpower requirements and virtually eliminates the need for scaffolding during the blast-cleaning and coating operations. However, the shop cleaning and priming procedure has drawbacks. A major drawback is that full-time inspection is rarely available, at least on small- and medium-sized fabricating jobs. Thus, shop inspection may be limited. Little can be determined concerning surface preparation and paint application after the work is done. Another major drawback is that shop coating results in a lengthened waiting period between priming and subsequent application of field coats. During this period the primer coat becomes hard and weathered, and it can become contaminated with dust, grease, and other surface soils that are detrimental to the adhesion of any subsequent coats. Long field storage periods tend to increase the opportunity for marring and scratching of the primer coat and, in extreme cases, may lead to its general deterioration. The paint application section of CWGS 09940 requires shop-coated steel to be stored out of contact with the ground and in a manner that will minimize the formation of water-holding pockets. This provision is considerably important. The shop coat of curved tainter gate sections field stored for months with concave surfaces up has on occasion deteriorated and rusted appreciably during storage as a result of water standing in the depressions. This is an understandable reaction because linseed oil paints are entirely unsuited for extended immersed exposure in a storage area. The guide specification additionally states that shop-coated steel shall be cleaned and repainted or touched up whenever it becomes necessary to maintain the integrity of the coating paint film; this requirement also is important.

In one known case, shop-coated steel was stored at the construction site for more than 18 months, and the provision to periodically touchup and repaint was not enforced. Consequently, at the time of erection the steel was in such poor condition that it required extensive cleaning and the application of a new primer coat, for which the contractor put in a claim for additional payment. This raises the question about what criteria should be used by field inspection personnel in determining if the shop coat needs touching up or a complete renewal. (Chapter 6 will be particularly helpful to inspection personnel in determining what type of corrective action is necessary.)

(a) Other shop problems and mishaps also have been observed. Air in heated shops warms more quickly than the steel surface; and, because the relative humidity increases as the air warms, condensation on the steel is possible. Paint is sometimes stored in a cold, unheated room and under such cool conditions can become very viscous. The resultant cold, thick coating may cause the applicator to thin the material excessively to reduce the viscosity and make it more sprayable. Excessive thinning reduces the volume solids of the coating and results in a lower dry film thickness and inadequate substrate protection.

(3) Shop primed plus field topcoated. A compromise may be found between accomplishing the work entirely in the field or entirely in the shop. This entails performing blast cleaning and applying the prime coat in the fabrication shop. The topcoat and any intermediate coats are applied in the field. This compromise includes the advantages from performing the work in the fabrication shop and the advantages with field application. Unfortunately, although there are advantages, such compromise is also not without shortcomings.

(a) The most obvious advantage to a compromise procedure is that the steel arrives at the jobsite with at least some degree of protection. Contamination of the steel substrate has not been eliminated because the prime coat may become contaminated while the steel is in transit to the site, in storage, or during construction. This is especially true if the steel is exposed to an industrial or coastal environment. Solvent wiping or high pressure washing of the prime coat prior to the application of further coats of paint may be specified to remove contaminants.

(b) Touchup of the prime coat generally is required to repair damage incurred in transit or during construction. Field welds, nuts, bolts, and areas around bolted connections also must be addressed. Surface preparation is vital. Some coatings (such as alkyds) may require only hand-tool cleaning; other coatings (i.e., zinc-rich coatings) require the type of surface preparation that can be achieved only by abrasive blast cleaning. Experience has shown that as much

as 30 percent of the surface area of water tanks often needs touchup, and some bridges may require only 10 percent touchup. Occasionally, the question arises about whether the responsibility for touchup lies with the fabricator or the contractor in the field, and how much touchup the responsible party should be required to perform. Accordingly, adequate field touchup should be clearly outlined in the project specification and understood by the parties responsible for the work.

e. Identifying surface preparation alternatives for maintenance. Based on the decision to maintenance paint an item or structure, several maintenance recoating alternatives may be considered: spot priming only, spot priming followed by full overcoating, or total removal and replacement. This paragraph will discuss the alternative methods of surface preparation that can be used in conjunction with these maintenance recoating methods. (See Chapters 6, 7, and 8 for additional information.)

(1) Spot priming only. Prior to spot priming, the mechanism of spot surface preparation and the cleanliness to be achieved must be determined. Spot preparation is required to remove localized areas of visible corrosion and/or loose, deteriorated, or poorly adherent coatings. Prior to general surface preparation, any grease and oil contaminating the surface should be removed by solvent cleaning in accordance with SSPC-SP 1. General surface preparation techniques such as abrasive blast cleaning and hand- or power-tool cleaning have a tendency to spread and/or redistribute grease and oil on the surface rather than removing it. Spot removal of loose coating, loose rust, and loose mill scale can be accomplished by hand- or power-tool cleaning or spot abrasive blast cleaning.

(2) Spot priming followed by full overcoating.

(a) The mechanisms of spot surface preparation given in the previous paragraph can be used if this recoating alternative is chosen. However, the method of preparing intact, well adherent coatings for overcoating must be addressed. The primary concern in overcoating an existing coating system would be system compatibility. The compatibility of recoating systems could be assessed by preparing a test patch. After an overcoating system is found to be compatible with the existing coatings, methods should be used to remove surface dirt, chalk, grease, oil, and other surface contaminants. These methods include solvent cleaning, pressure cleaning with detergent at less than 34,450 kiloPascals (kPa) (5,000 psi), high pressure water jetting with detergent (34,450 to 137,800 kPa [5,000 to 20,000 psi]), high pressure water cleaning (34,450 to 137,800 kPa [5,000 to 20,000 psi]) with abrasive injection, ultra-high pressure water jetting (137,800 to 275,600 kPa

[20,000 to 40,000 psi]) with abrasive injection, or brush-off blast cleaning using fine sand and low abrasive blasting pressures.

(b) Glossy, hard, smooth, or slick existing coating systems may require roughening to promote adequate adhesion. Hand- or power-tool roughening of the existing coating may be done by using hand- or power-tool methods such as sanding. The surface gloss must be removed and the visible surface roughened after preparation. Brush off blast cleaning (SSPC-SP 7) also may be used to clean and roughen the existing coating using the methods outlined here.

(3) Complete removal and replacement. If the recoating decision process has found that the most economical and practical option is complete removal and replacement of the existing coating, the following surface preparation methods may be used. These alternatives in conjunction with the desired surface cleanliness will produce a substrate that essentially can be recoated as a "new" surface. Standard abrasive blast cleaning, high pressure water jetting with abrasive injection, ultra-high pressure water jetting with abrasive injection, or wet abrasive blast cleaning to the desired cleanliness may be used to completely remove the existing coating. When blast cleaning cannot be used, power-tool cleaning to bare metal (SSPC-SP 11) can be used to remove old coatings.

f. Identifying coating application alternatives. In addition to surface preparation alternatives, coating application alternatives should be explored. Local regulations on spray application of coatings (proximity to roads/highways, parking lots, residential areas) may restrict the application method used. Brush or roller applications may be required, which may restrict the choice of coating system used because certain coating systems do not lend themselves to application methods other than spray (e.g., vinyls, inorganic zinc-rich primers). Some coatings (referred to as "dry falls") are formulated so the overspray during atomization dries prior to landing on an undesirable resting place.

g. Cathodic protection system as an alternative. The primary function of cathodic protection and coatings is to prevent corrosion. As corrosion protection has become more critical, a marriage of the two processes has occurred. Experience has shown that damage to organically coated surfaces is almost unavoidable during construction and in service. Cathodic protection frequently is used in conjunction with coating systems and immersion service where breaks and holidays in the coating expose an unprotected metal substrate. Protecting some structures in these environments may be difficult, if not impossible, with

coating systems alone, especially on complex, configured structures. Thus, the combination of coatings and cathodic protection actually provides good, reliable corrosion protection. USACE has found cathodic protection systems in conjunction with CTE systems to be excellent choices in this regard. (Detailed information on cathodic protection is given in Chapter 2.)

5-3. Coating Selection Criteria

The final selection criterion is to determine how effective the coating system will be in preventing corrosion of the underlying surface in the service environment. Clearly and accurately defining the service environment, soliciting coating manufacturers' recommendations, applying test patches of candidate coating systems in the service environment, and obtaining a successful field history of a generic coating system in an identical or similar service environment will enable the coating specifier to select the coating system that will provide long-term protection of the plant and/or facilities.

a. Supplier recommendation. Major manufacturers of coatings and coating systems typically have invaluable information on application parameters of their coating systems, both in terms of temperature restrictions and chemical resistance. Therefore, the suppliers of coating systems should be asked about information on the types of products that will perform in the service environment(s) identified. However, most manufacturers do not have exhaustive information on every service environment that may be encountered; and previous experience with a given coating system in a certain environment may not always be available. Also, some suppliers may not have information because they are not familiar with Government specification paints unless they are actual producers of them. In these instances, a test patch applied and evaluated in accordance with ASTM D5064 at the location of intended service is highly recommended prior to large-scale application.

b. Ease of application. The ease with which the coating can be applied will impact applicator productivity and coating film integrity. That is, if a coating material cannot be applied without complicated equipment and specialized techniques to produce a continuous, void-free film, it may not be cost effective to apply such a system unless, of course, the service exposure demands such a system. Therefore, ease of application should be an important consideration during coating system selection.

c. Maintainability. The maintainability of a coating system is another factor to be considered, and how it will be maintained (by outside contractor or by plant personnel). If plant personnel are responsible for coating system

maintenance, it is imperative that they be familiar with any specialized equipment or application techniques and properly trained in their use. The surface preparation that will be required during maintenance painting also must be considered. It may be as simple as a solvent wipe (SSPC-SP 1) and reapplication, or as extensive as scarification (SSPC-SP 3 or SP 11) or abrasive blast cleaning of the surface followed by application of the repair system.

d. Cost. Appropriate coatings systems selection must take into account paint performance as well as paint economics and balance performance against total cost. Top quality coatings should be compared generically, but identification by generic name in itself is no guarantee of quality. Coatings should be purchased on specifications from reliable coating manufacturers. A protective coating should not be purchased unless its volume solids content and the resin content of the solids are known. Economics plays a key part in selecting a coating system. In fact, under some circumstances, economics may determine the system choice. Therefore, coating costs, in most instances, should be less important than the coating properties that provide the basis for long-term, effective coating protection. Costs should be considered only after the coating or coatings have been selected that will satisfactorily overcome the corrosion problem for which they will be used. For example, during the selection process, two or three coatings all may have the necessary qualifications. Cost then can determine which of the coatings that entirely satisfy the conditions involved will be the most economical choice. Additionally, the cost of the coating system depends on the generic type, the spread rate, the ease of application, maintainability, and projected service life of the system. When choosing the most economical coating system, factors for determining this suitability may include the following.

(1) Environmental resistance. Coatings will be cost effective only if they are used within the limits of their environmental resistance. If an environment is too severe for a coating, that coating will require expensive maintenance, and a different coating material or construction material should be used.

(2) Duration of protection desired. Most coating materials will deteriorate because of their organic or sacrificial nature, and they will require maintenance and periodic renewal. The length of time required for refurbishment may be less in some environments than in others. The cost and difficulty of refurbishment or replacement must be assessed to arrive at the appropriate coating or construction material.

(3) Surface preparation required/allowed. Most coating

systems must be applied over a relatively clean substrate such as that obtained by blast cleaning, grinding, or acid etching. If the required surface preparation is not economical, the use of other construction materials may be more cost effective (i.e., stainless steel, plastics).

(4) Application/curing conditions. If ambient conditions cannot be made suitable for the application and/or cure of the coating system, other means of corrosion protection must be considered (i.e., cathodic protection).

(5) Availability of labor/material. The application of coatings is labor-intensive, and if sufficiently skilled equipment or labor is not available, the cost effectiveness of using protective coatings may be reduced.

(6) Health and safety considerations. Solvents, resins, and certain pigments in coatings may be hazardous to personnel applying the protective coating or the safety and health of personnel in the surrounding area. Safety, health, and environmental considerations at the time of original application and during touchup and repair may be sufficient to reduce the cost effectiveness of coatings compared to other construction materials.

(7) Mobilization/demobilization. There are costs associated with bringing equipment, material, and labor to a jobsite. The costs for transportation and setup of equipment are commonly called mobilization costs. The costs to remove equipment and material from a jobsite are called demobilization costs. These costs can be considerable on large projects, and they must be considered in assessing the costs of a coatings operation. For fixed-site coating facilities (i.e., paint shop) the item to be coated must be transported to and from the shop. These costs may be significant and should be included in cost estimates.

(8) Access costs. The cost of rigging, scaffolding, or otherwise gaining access to the work area can be expensive, particularly when coating a large bridge, water tank, or elevated structure.

(9) Preparation costs. Prior to actually starting surface preparation and/or coating work, certain preparation costs must be assessed. The cost to mask or otherwise protect items not to be painted, to grind or round sharp edges, to enclose the work area, or to protect adjacent work areas or the environment can all be considered preparation costs.

(10) Coating system installation costs.

(a) Coating material costs. Coatings are usually supplied in 1-, 5-, or sometimes 55-gallon containers, and they generally are invoiced at a dollar cost per gallon. These

costs may be considerable on a large job; and, as a rule of thumb, they range from 10 to 15 percent of the cost of the total jobs. However, the coating material cost may be a substantially higher percentage of the total cost if other costs (i.e., surface preparation) are minimal. Rather than the cost per gallon, some specifiers consider the system cost per square foot (i.e., the cost to cover a given area at the required film thickness). Thus, a coating system that builds to a greater thickness in one coat, or has a higher percent solids by volume, ultimately may be cheaper even if the cost per gallon is higher than another material. In this case, application labor would be saved because fewer coats would be required to attain a given thickness. Other specifiers consider cost per year of service life. The evaluation incorporates the expected service life of the coating system in the assessment of its cost. Therefore, a coating that costs \$10 per gallon and lasts for a year will be more expensive than a coating that costs \$20 per gallon but lasts for 5 years. The most comprehensive assessments consider the system cost square foot per year and try to optimize both application savings and service life longevity.

(b) Coating application costs. Labor time associated with the actual application of the coating must be considered. The number of coats required is a major factor in establishing this cost as each coat application is a separate operation. The cost of application labor is a major expense on most jobs, usually second only to the surface preparation.

(c) Surface preparation costs. The labor cost of surface preparation is a major consideration for all coating work. The costs for surface preparation can vary considerably, depending on the method and the extent of surface preparation requirements. As a general rule, when blast cleaning or using other thorough degrees of surface preparation, the costs of labor and equipment may approach 40 to 50 percent of the entire cost of the project. The surface preparation required usually is determined by type of coating system chosen for application. Some coating systems (i.e., vinyl, inorganic zinc rich) require thorough, labor intensive surface preparation such as that by blast cleaning to "White" or "Near White" metal cleanliness; other coating systems are more tolerant (i.e., epoxy mastics) and may not require as thorough, or as expensive, a degree of surface preparation. However, the service life of virtually all coatings is increased by a greater surface cleanliness.

(d) Equipment costs. The cost of wear and tear on surface preparation equipment and application tools and equipment (including operational and maintenance costs) must be considered. Rental rates that can be used as a guideline for equipment costs frequently can be obtained from equipment rental companies.

(e) Curing/drying considerations. Some coatings require an extended cure time prior to being placed in service. Heat curing may be required for certain coatings used as tank linings. If required, special curing conditions may increase the cost of the coating system.

(f) Trade or craft interference/downtime. The coating application process (e.g., surface preparation) is time consuming and may require traffic control, stoppage of operating equipment, or downtime in the immediate vicinity of the work area. Also, nearby workers may object to the noise, odors, and potential hazards associated with the coating operations. Those indirect costs also should be evaluated when considering coating work costs.

(g) Environmental/health and safety costs. Environmental, health, and safety factors are extremely important and may be difficult to assess, but potentially they can be expensive. The Federal Government, most states, and many local communities have strict environmental laws that must be obeyed. Similarly, in the area of worker protection, OSHA requirements must be obeyed on any painting job. The cost of compliance during field painting may be high in comparison to another construction material or another means of corrosion protection. Compliance may be easier during painting in the shop as opposed to painting in the field. Compliance considerations ultimately may be among the most important cost considerations. Environmental protection costs can be as much as, or more than, all of the other costs combined. (Chapters 10 and 11 provide additional information on this subject.)

(h) Indirect costs. Painting projects, as is true with most other construction or maintenance projects, must be properly planned and require specifications, proper management, and adequate inspection to ensure specification conformance. Although these costs also must be considered when evaluating other methods of corrosion protection, they are vital considerations for all coating projects.

(11) Cost estimation and decision making. Preparing accurate estimates of the cost of painting is not easy, and even professional estimators working for painting contractors sometimes estimate inaccurately. Most cost estimates are based on one or more of the following: an estimation of the surface area to be painted, an estimation of costs per unit surface area, an estimation of the man-hours required, and an estimate of the materials and equipment costs.

(a) Surface area to be painted. The surface areas of each item to be painted are measured or estimated, and the cost of painting per unit area (i.e., a square foot) is then applied to achieve a total painting cost. For example, if an area to be painted has a number of pipes of various diameters,

doors, windows, floors, pieces of equipment (e.g., tanks, pump housings, fans, and motors), structural steel, and overhead truss work, the total surface area of each of these items would be estimated or measured. Books and tables are available for estimators to use when making unit area (square foot) calculations. The Painting and Decorating Contractors of America (PDCA) estimating guide provides tables for calculating unit areas in square feet as well as labor rate figures for coating each of these unit areas. After the square footage has been calculated, the time required to conduct surface preparation and/or paint application also must be calculated for each unit area for each category of work (i.e., speed at which a wall or floor can be coated might be entirely different than the rate for coating a series of 76-mm [3-in.] pipes). Thus, appropriate labor rates for each work item should be applied to the unit area of that work item. The cost for unit area multiplied by the total area within each category provides the total cost of painting when all categories are summed.

(b) Man-hour estimates. Many nonpainting operations are part of the overall costs of coating work. For example, mobilization/demobilization, rigging and scaffolding, time for inspection, time for cleanup, and time for equipment maintenance all must be considered when estimating costs. These costs usually are estimated in man-hours or man-days by the estimator. By knowing the particulars of the project, including its size, shape, completion date, and areas to be coated, the estimator can approximate the size of the crew and the equipment required. With this information, a knowledgeable estimator will prepare a schedule sequencing a work order for the job. The work order will indicate when moves must be made from one area to another during the course of the work. The nonproductive costs associated with each move (i.e., transported equipment, rigging, or scaffolding) then can be estimated for each move and applied to the total job costs. Similarly, during the painting operations, other costs (for inspection, cleanup, touchup of defective or damaged areas, maintenance of equipment, etc.) also should be included. These costs usually are estimated in man-hours per unit operation. The estimator evaluates the work to be done and estimates the man-hours needed to complete it. The surface area being painted is not calculated.

(c) Wage rate. The wage rate of most workers usually is known, but the speed at which they work is difficult to estimate. Estimates of labor rates are in estimating guides; however, most painting contractors and experienced coating estimators know by experience what work productivity rates are. Most painting contractors and professional estimators use their own labor rates and do not rely on estimating guides. However, most specifiers use the labor rates presented in estimating guides.

(d) Cost of materials and equipment. The number of gallons of paint, thinner, cleanup solvents, etc., must be estimated, based on the square footage of the areas being coated and estimated loss factors during the course of application. Material loss factors, including overspray and materials remaining in the can, generally range from 20 to 50 percent of the total paint purchased, depending on weather conditions and the type of surface being coated. Based on these estimates, the total amount of paint to be ordered and used on a job can be calculated. The cost of the equipment used on a job also must be estimated and might include charges for the use of compressors, spray guns, airless or conventional spray pots or guns, air and paint hoses, etc. Fuel costs for diesel compressors and electrical generators (if required) also must be estimated. Most painting contractors have developed standard cost estimates for items such as diesel fuel and electrical consumption and can estimate these rates on a daily, weekly, or monthly basis. These equipment/material costs must be factored into the cost of painting. The cost of consumable supplies and equipment must be estimated; abrasives, cleaning rags and cloths, respirators or respirator cartridges, overalls or protective clothing, masking tape, and small tools such as scrapers or wire brushes are all considered expendable consumable items. The cost of these items must be estimated and applied to the total cost of the job. When each cost category is properly estimated and totaled, the comprehensive budget estimate for the painting job can be made. Costs for overhead, insurance, licenses, taxes, etc. must be added to the direct cost to arrive at a total cost.

(12) Alternate ways to prepare coating budgets. Rather than taking the time and making the effort to detail the costs of a painting project as described here, many estimators budget coating work by other means. These estimates are generally less accurate and may be subject to some bias. The accurate determination of painting costs is important to management's decision to provide budget funds for painting operations. Some commonly used budgeting techniques are given here:

(a) Budget estimates for the current year based on the cost of painting conducted in the previous year. Budget estimates may be allocated on a "total funds" concept whereby a certain percentage of maintenance funds are attributed to maintenance painting.

(b) Funding allocations—whether new construction or maintenance painting—only a certain amount of funding is set aside for coating work. No real budget estimates are made, and work is done by either a contractor or in-house plant painting force until the funds are depleted.

(c) Contractor estimates—items or areas to be painted are determined, then one or more painting contractors are asked to provide a cost estimate to conduct the painting work.

(d) Single-source painting programs—some coating manufacturers and independent coating consultants have established single source painting programs whereby a contract is extended to the plant or facility owner (usually at a certain cost per year over a multiyear period). For the contracted cost, a complete painting program is established, and all painting work is conducted. Detailed budget estimates are made by the single-source contractor rather than the facility owner. The facility owner is given an annual cost amount for painting to include in his maintenance budget.

(e) No budget estimate—some owners do not prepare budgets but contract with a friendly local painter or use their own work force to paint on an "as needed" basis. Costs are invoiced, usually on a monthly or weekly basis. At the end of the painting season, the amount expended for painting work can be totaled.

(13) Life cycle costs of coating systems. Accurate budget estimates should be made for each of the corrosion protection methods to be considered. The budget estimates should include costs for the initial work as well as for all future maintenance activities to obtain a "life cycle" cost. For example, initially the cost of installing a stainless-steel-clad lining to a tank may be twice as much as painting the tank, but over a 20-year expected life there may be no maintenance costs. So although it may cost half as much to paint the tank interior as to use a stainless-steel lining, the tank will need to be repainted every 5 years. Thus, over a 20-year-life cycle of the tank, it will cost twice as much to paint the tank as it would to protect it with a stainless-steel cladding. However, when cash flow is slow, painting may be the most economical means of corrosion protection. If a decision to paint is made, a hope may be that future cash flow or profitability will improve and enable the payment of expected higher future maintenance costs. Factors involved in decision making are complex and specific, and they vary considerably because of return on investment strategies, tax considerations, cash flow availabilities, potential for technological advancement, legislative restrictions and marketing, or sales analyses. However, the costs of corrosion prevention alternatives (including painting) must be estimated properly to provide management with the proper tools to make a prudent decision. Thus, there are many alternatives available to the informed engineer to protect a structure. Ultimately, however, the economic selection of a particular system involves two criteria:

duration of effective protection and costs to obtain effective protection.

(14) Estimating the duration of protection.

(a) The length of protection of a properly selected and applied protective coating system will depend on the corrosive environment. Specific coating recommendations for a given environment can be subclassified as subjective and objective. The problem with subjective recommendations is one of credibility—whom to believe. The experience and biases of a person making the statement must be considered prior to accepting a solution to the problem. A subjective recommendation may be satisfactory for most small painting jobs or industrial application for which little money will be expended. However, for large jobs when substantial funds will be expended, or the consequences of failure will be serious, misinformation may be costly. As a result, evaluation of protective coatings using an objective approach may be desired. Objective evaluations of the protective life of a coating system are based on the observation of actual performance of coating systems in a given environment. If properly conducted, empirical evaluations generally are considered more accurate and usually provide the basis for knowledgeable recommendations. Objective empirical testing for convenience can be subcategorized into laboratory testing and field testing.

(b) Laboratory testing consists of standardized tests involving various atmospheric or immersion test chambers and devices for measuring flexibility, extensibility, adhesion, scratch or impact resistance, and other coating characteristics. Field testing involves coatings exposed in a nonlaboratory corrosive environment; examples are test sections on a bridge or water tank or coated test panels placed in various corrosive environments. Generally, laboratory testing precedes any field testing. During the course of either laboratory or field testing, the coating being tested is observed to determine its mode and rate of failure.

(c) Laboratory tests frequently are designed to accelerate failure conditions found in the field to reduce the time of coating failure to a reasonable period (usually about 30 to 60 days). Acceleration usually is accomplished by increasing the exposure extremes or increasing the frequency of exposure to corrosive elements (such as salt fog cabinets and weathering cabinets in which a cycling exposure of water and UV light repeats every hour or so). Both the exposure extreme and the frequency of exposure may be combined in one test (such as reagent or immersion tests for coatings that in service are not expected to withstand strong chemical or immersion conditions). These tests will give a "ranking of performance" and provide a screening, but not necessarily a "duration of protection." Generally, the best

performing coating specimen in a laboratory test series will also perform well in actual use. However, this is not always a valid assumption. Actual field testing is often the preferred and most accurate method to provide an estimate of duration of protection, which is generally expressed in months or years.

(d) Most field tests are not accelerated tests but are coating exposures in the actual (or similar) service environment in which the coating is expected to be used. Therefore, failure is not accelerated. Coating systems being tested will deteriorate at the same rate as the coating will be expected to deteriorate in actual service under the same conditions. Field tests may not be fully representative of field conditions if there are environmental changes, mechanical or flexural influences, and other factors that are not adequately induced into the test protocol. Because coating systems for atmospheric exposure protect for 15 years or more, real time testing to "failure" is not practical. However, close observation of candidate coatings and their comparative rate of degradation will enable selection of the best coatings prior to complete failure. This observation is commonly done in field testing and when using test panels. Suitable selection criterion can be obtained within 6 to 24 months for many systems. The best method of determining the extent and duration of protection is to observe and record the failure history of a given system in actual use. If care is taken and proper records are kept, this determination can and should be done for every protection system in use. Unfortunately, information thus obtained often becomes obsolete as superior coatings and protective methods become available and technology advances.

5-4. Service Environments for USACE Structures

Of primary importance in coating selection is the degree of surface cleanliness. Proper surface preparation is necessary to create a satisfactory level of adhesion between the applied coating system and the substrate. Adhesion is a key characteristic affecting coating performance. Various generic coating types may achieve adhesion by different methods. For example, the coating may form a protective thin film by merely lying on the surface, or there may be a chemical reaction with the substrate. Good coating adhesion is an essential coating characteristic and becomes even more important as the aggressiveness of the exposure environment increases. When properly applied, a coating's rate of success is directly in proportion to its adhesive bond strength. As a result, various USACE exposure environments will be discussed below with regard to the minimum surface preparations required to provide adequate adhesion for the various exposures. Four exposure environments can be used to categorize a vast majority of

USACE painting projects: interior; atmospheric, normal weathering; atmospheric, severe weathering; and immersion or frequent wetting by splash, spray, or condensation from fresh or salt water. Although immersion and frequent wetting initially may appear to be different exposures, experience shows that, generally, the same generic coating systems are successfully used in both exposures. The information on selecting a coating system discussed earlier in this chapter will be particularly helpful in identifying coatings that will perform well in these exposures.

a. Interior exposure. Interior surfaces are classified as those that are located within weather-tight structures and are not exposed to atmospheric elements. Although the majority of these exposures are mild, there may be circumstances under which conditions may alter an environment and a more corrosion-resistant coating may be required. For example, unanticipated leakage or equipment malfunctions may result in added environmental stresses, such as condensating moisture or high humidity within an otherwise "normal" environment. Additionally, areas or items that, for various reasons, may become inaccessible after installation or construction should be carefully coated to assure that a coating system for adequate long-term protection is applied. Interior exposure is the mildest exposure environment a coating will encounter. Products used on interior surfaces may be used for aesthetics or decorative purposes only. However, in some instances a coating system must be able to perform in areas of frequent cleaning and scrubbing (i.e., high traffic areas, restrooms). Generally, there are restrictions on the type of preparations that can be performed indoors. There are few, if any, extraneous influences that could stress a coating under circumstances to adversely affect adhesion. However, care must be taken to choose coating systems that are compatible with each other and the substrate to which they are applied. Particular assistance in this regard is discussed in Chapter 4.

b. Atmospheric, normal weathering. Weather resistance is the key variable in atmospheric exposures, but this environment can be extremely complex. A coating in atmospheric exposure must be capable of withstanding a variety of conditions that include cyclic heating and cooling, airborne contamination, alternate wetting and drying, UV resistance, and maximum exposure to the deteriorating effects of oxidation. Exposures also may vary from hot, dry climates and humid, tropical environments to constantly cool or cold climates. Therefore, a coating system capable of withstanding a variety of exposure conditions is essential. With strong adhesion qualities, the coating can withstand most environmental stresses that otherwise would affect its integrity.

c. Atmospheric, severe exposure. A salt-laden marine

environment or a heavily contaminated industrial exposure is extremely corrosive. Coatings with increased resistance to these environmental conditions are required. These types of exposure conditions are considered to be moderate to severely corrosive to a coating system, and coating systems must be selected accordingly.

(1) When a weathering environment becomes further complicated by the addition of severe exposure elements (e.g., corrosive chemicals, high humidity, severe abrasion, or salt conditions), more sophisticated surface preparation techniques must be used. These added exposure elements will stress the coating system at the point of weakest adhesion. The coating must exhibit good adhesion, and a high order of coating resistance will be required (e.g., a two-part epoxy or urethane coating). As the service demands on a coating system become greater, so does the need for more thorough surface preparation. Abrasive blast cleaning is required to achieve optimal cleanliness and adhesion.

(2) New generation two-part surface tolerant epoxy mastic coatings are gaining rapid acceptance in severe atmospheric exposures. Technological advances within the protective coating industry have brought about development of coatings that exhibit excellent surface wetting characteristics, rust inhibition, abrasion resistance, and chemical resistance. These mastics can be applied to marginally prepared surfaces, such as hand-tool or power-tool cleaning, and show improved service life in situations in which abrasive blast cleaning may not be feasible. Although epoxy mastics provide improved performance, they do not perform as well as equivalent paints applied to a higher degree of surface preparation. As a general rule, the more severe the environment encountered, the more resistant the coating must be; consequently, the more precise the surface preparation requirement becomes.

d. Immersion or frequent wetting exposure.

(1) Most immersion or frequent wetting of USACE structures involves exposure to fresh water or seawater. The effect of water on most coating materials is extremely severe. Resistance to water is perhaps the most important coating characteristic because all coatings come into contact with moisture in one form or another. Water, which affects all organic materials in some way, is actually close to being a universal solvent. Therefore, no one coating system can be effective under all water conditions. For example, dam gates and trash racks may require a coating system different from that of the flume bringing water into the dam. Additionally, different types of water may be encountered, such as deionized acidic or sulfide water. Highly conductive water, such as seawater, leads to rapid formation

of anode/cathode areas on the steel that result in severe pitting. The rate of corrosion is proportional to the amount of oxygen in the water; water with a high oxygen content will create similar anode cathode corrosion areas. Therefore, no single type of material will provide a universal answer to coating problems. The water molecule is extremely small and has the ability to penetrate into and through most inorganic compounds. The water molecule passes through the intermolecular spaces of the organic material and either can remain there in an absorbed state or can pass through the compound. Moisture generally will come to an equilibrium, with as many water molecules passing into the organic material as evaporating out of the surface. So a relatively constant water content is maintained in the organic material, depending on the moisture vapor at any given time.

(2) Because of this highly penetrating characteristic, water has more of an effect on organic compounds than any other material. Because most coatings are organic in nature, they must have the highest possible moisture resistance to maintain their properties and provide their structure with a long period of corrosion protection. For a high performance, corrosion-resistant coating to have a water resistance, it must withstand continuous immersion in water or seawater, and it must do so without blistering, cracking, softening, swelling, or loss of adhesion. It also must withstand repeated cycles of wet and dry conditions and abrasion from floating ice and debris. Coatings tend to absorb and retain water in their molecular spaces, and each coating has a level of water absorption. If a coating is strongly adhesive and there is no interface between the coating and the substrate, the moisture will remain in a relatively inert state. At any given moisture pressure, as many molecules leave the coating as enter it. Thus, the best corrosion-resistant coatings generally have the lowest water absorption rates (e.g., CTEs, vinyls, and inorganic, zinc-rich coatings).

(3) The moisture vapor transfer rate is the rate at which moisture vapor transfers a protective coating when there is a difference in moisture vapor pressure on one side of the coating compared to the other side. Each coating also has a characteristic moisture vapor transfer rate. Generally, the lower the moisture vapor transfer rate, the better the protection provided by a corrosion-resistant coating. The transfer of moisture through a coating depends on the difference in pressure between the two sides of the coating. There is no difference in pressure from one side to the other if the coating has excellent adhesion, and the coating soon comes to equilibrium with the moisture in the air or the water in the surface of the coating. The water molecules penetrate into the coating and are absorbed while an equivalent number are evaporated from the coating, so the amount of moisture in the coating remains constant.

(4) If the coating has poor adhesion, either inherently or because it has been applied over a contaminated surface, there is an interface between the coating and the steel (as in dam gates and trash racks) and moisture vapor can transfer into this area. Soon after the coating is applied, there is little moisture vapor pressure on the interface area, so there is a tendency for moisture to pass in the direction of the poor adhesion. Moisture can condense in this space or, if the temperature of the coating increases, the moisture vapor within the void can develop sufficient pressure to create a blister. With poor adhesion, the moisture vapor can penetrate between the steel and the coating, expanding the blister.

(5) The primary requirements for coating to be used for immersion are good adhesion and resistance to moisture vapor transfer, ionic penetration, osmosis, chemicals, cathodic disbondment, and variations in temperature. Snow water, distilled water, or deionized water are close to if not the most penetrating of all the chemicals in which a coating is immersed. But, as the content of the water is increased it becomes more aggressive; primarily because it is much more conductive and corrosion can take place at a much more rapid rate. Although it is commonly known that seawater is aggressive, polluted fresh water may be more destructive to coatings than some seawater. When choosing a coating system for an immersion environment, the conditions should be precisely determined prior to selection. Even solutions with minor contaminants that were scarce enough to be deemed unimportant have caused many coating failures in immersion conditions.

(6) Protecting metallic structures immersed in fresh water is a complex problem. However, when the additional corrosive elements in seawater become apparent, the destructive magnitude of this exposure environment becomes considerably more intricate and complex. Structures immersed in seawater, like their freshwater counterparts, naturally experience multiple exposure environments. The salinity of seawater and its associated high electrical conductivity, along with the surface growth organisms, greatly contribute to the overall corrosivity of seawater. These organisms become destructive when they attach themselves to, and physically penetrate into, a coating film. This growth process is commonly known as fouling; coatings developed to prevent or inhibit this process are called antifoulants. Unfortunately antifoulant coatings are not formulated with exceptionally long service lives, primarily because they are used to prevent marine organisms from fouling on smooth and regular surfaces of ships at rest. Since ships are frequently dry docked, and cleaning and repainting operations can take place, the need for antifoulant coatings with an extended service life is not necessary. Initially, antifoulants would appear to be a logical system choice for USACE structures with similar exposures.

However, on closer examination and through experience with questionable performance of antifoulants applied to irregularly shaped fixed structures (such as gates), this system option has not proven to be highly successful. Therefore, choosing antifoulant paints as a coating system for some USACE structures should be carefully considered. A discussion of coating systems for structures immersed in seawater would be remiss if it did not also reference splash zone or surfaces continually wet by well aerated seawater. Experience has shown that paint films normally deteriorate more rapidly in splash zones than in other zones, primarily because the abundance of oxygen fuels the corrosion process.

(7) Coating systems applied in such environments as immersion or frequent wetting exposures require a high degree of surface preparation. The minimum requirement is generally that presented in SSPC-SP 5. All forms of surface contamination, including possible chloride contamination from salt water, must be removed, and coatings formulated for the required immersion resistance need to be used. Coatings that typically perform well in immersion or frequent wetting exposures are discussed in Chapter 4.

5-5. Coating System Selection for Ferrous Components in Fresh Water

a. Ferrous metal components.

(1) Current alkyd coating systems required in CWGS 09940 (systems 1 and 2) are: alkyd primer/phenolic aluminum paint (two coats), rust-inhibitive linseed oil and alkyd primer (two coats), and rust-inhibitive linseed oil and alkyd primer/alkyd gloss enamel (two coats). Because these coating systems are for mild interior exposures and basically consist of primer only formulations, they are readily touched up. Surface preparation may be performed by hand- or power-tool cleaning.

(2) Candidate maintenance systems would be new technology versions of direct-to-metal (DTM) 100 percent acrylic waterborne industrial coatings and higher solid VOC-compliant alkyd primer systems.

b. Ferrous metal components subject to atmospheric weathering—normal.

(1) Current coating systems. Current alkyd coating systems required in CWGS 09940 (systems 1 and 2) are: linseed oil primer/phenolic aluminum (two coats) and linseed oil and alkyd primer/phenolic aluminum (two coats). In this normal atmospheric weathering exposure, many

formulations of alkyd generic coatings would perform satisfactorily.

(2) Candidate maintenance systems. Candidate maintenance systems would be high solids VOC-compliant lead- and chromate-free versions of alkyd primers and finish coats. Most existing alkyd systems can be successfully recoated with long oil alkyd resin systems. Additionally, DTM waterborne, 100 percent acrylic primers and finishes are successful in overcoating existing or aged alkyd systems. New generation acrylics provide more superior gloss retention, color retention, flexibility, and weatherability than traditional alkyd systems. Water-reducible alkyd systems also have found market acceptance; however, their performance characteristics do not rival those of DTM acrylics.

(3) Candidate systems for new steel. Candidate systems for new steel would be high solids VOC-compliant versions of exterior alkyds both waterborne and solvent reducible. Strong competitors to the traditional alkyd systems are the new generation waterborne acrylic industrial primers and finish coatings. Much like their alkyd counterparts, waterborne acrylic coatings are easy to apply and relatively inexpensive, but have the added advantages of improved gloss retention, weatherability, and low odor.

(4) Special concerns and cautions. Portions of these alkyd coatings applications will be done in the shop. Surface preparation for a normal atmospheric weathering exposure is commonly accomplished by complying with SSPC-SP 1, SSPC-SP 2, or SSPC-SP 3. Of primary concern is that these ferrous metal components are often shop-primed and placed in storage for an extended period prior to final erection and finish coating. Untopcoated, these primers do not possess good weatherability; therefore, appropriate precautions must be taken to properly protect the structure while in storage. Adequate protective coverings to protect from moisture and debris accumulation on the substrate are necessary. Additionally, proper blocking and stacking techniques should be used to avoid ground contact in storage. Prior to erection and before finish coating, a careful inspection will be necessary to identify deficiencies (such as prime coat handling or erection damage) and for preparation and touchup as appropriate.

c. Ferrous metal components subject to atmospheric weathering—severe.

(1) Current coating systems. Current alkyd coating systems required in CWGS 09940 (systems 1 and 2) are: linseed oil primer/phenolic aluminum (two coats) and linseed oil and alkyd primer/phenolic aluminum (two coats).

Other systems would be those as identified in 5-5b above, with the special concerns and cautions identified in item 5-5c(4) below.

(2) Candidate maintenance systems. Candidate maintenance systems would be those described in 5-5b above, with special concerns and cautions as identified in 5-5c(4) below.

(3) Candidate systems for new steel. Candidate systems for new steel would be those previously described in 5-5b above, with the special concerns and cautions as identified in 5-5c(4) below being applicable.

(4) Special concerns and cautions.

(a) The anticipated difference between normal weathering and severe weathering environments generally does not necessitate changing the coating systems. Traditionally, systems that perform well in "Atmospheric Weathering—Normal" environments also will perform under these "Atmospheric Weathering—Severe" exposures. However, the longevity of the system may shorten. Consequently, several options can be used within these normal and/or severe atmospheric weathering environments to improve system service life, e.g., improving the surface cleanliness or applying additional coats of paint. For example, applying a second coat of primer or another finish coat would improve the protective quality of the coating. Additionally, surface preparation may be upgraded to abrasive blast cleaning per SSPC-SP 6. However, there may be instances when a unique exposure will require a change in a generic coating type. These situations can be addressed on a case-by-case basis.

(b) There is no clear-cut parameter to describe a marine-exposure environment. Although corrosion is accelerated by the moisture- and salt-laden air, the degree of corrosivity varies from mild to severe. Generally, corrosion is intensified or decreased in proportion to the distance from the shore, with a rapid decrease in corrosivity as the distance from the shore increases. As with other severe atmospheric exposures, a mild marine environment can be adequately protected by improving surface preparation cleanliness or adding coating film build as previously described in 5-5c(4)(a) above. Because corrosion and film undercutting, especially at points of discontinuity in the coating film, are greatly accelerated in the presence of salt, locations close to salt water require special attention. Chlorides (salt) are often invisible contaminants, and their presence may go undetected. Salts can present complex problems in surface preparation if they are not successfully removed. Specialized test methods assure that chloride contamination has been adequately removed (see Chapter 9).

Because the salts are water soluble, common methods of removal are by steam cleaning or pressure water blasting. The methods should be accomplished prior to general surface preparation to prevent the redistribution of chloride contamination. In highly contaminated environments, the complete removal of salts and the upgrading of surface cleanliness are extremely important.

(c) Alkyd systems generally have been found to provide adequate protection in mild-marine environments, with corresponding improvements in surface preparation or added film build, as the severity of the exposure increases. In more severe exposures, as on complex structures in proximity to seawater, consideration must be given to choosing a generic coating of superior resistance. Experience has shown that vinyl systems perform well in these situations. Improved protection is noted when this vinyl system is coupled with an inhibitive zinc-rich primer.

d. Ferrous metal immersion and frequent wetting—fresh (inland waters) or prolonged wetting by splash, spray, or condensation.

(1) Current coating systems. Metallized systems requirements are specified in CWGS 05036. Current vinyl, CTE, and epoxy polyamide coating systems specified in CWGS 09940 are:

- Vinyl (four to five coats)
- Zinc-rich vinyl/vinyl (three coats)
- CTE (two coats)/CTE (two coats)
- Zinc-rich epoxy (two coats)/CTE (two coats)
- Epoxy polyamide (two to three coats)
- Zinc-rich epoxy (two coats)/epoxy polyamide (two to four coats)
- Systems which have performed well in "Immersion and Frequent Wetting—Fresh (Inland Waters) or Prolonged Wetting by Splash, Spray, or Condensation" environments which are not listed in CWGS 09940 are formulations of phenolics, coal tars, asphalts, NeoprenesTM, inorganic zinc-rich, and organic zinc-rich coatings.

(2) Maintenance painting. Maintenance painting, such as spot touchup, frequently is required to repair smaller failing or damaged areas on a structure. This process further lengthens the service life of a structure with an otherwise intact coating system. These maintenance repairs frequently are made to structures that cannot be taken out of service for long periods of time. Proper spot repair can

¹ DuPont Company, Wilmington, Delaware.

permit the structure to remain in service until it is feasible to shut down for complete maintenance repainting. Obviously, surface preparation techniques are limited and are generally on the order of those given in SSPC-SP 2 or SSPC-SP 3. Viable candidates for such nonpermanent repairs are solvent-based coal tars and surface tolerant, two-part immersion-grade epoxy mastic coatings. Keep in mind that these repairs are considered only temporary to preserve the structure until proper blast cleaning and recoating with a system shown in CWGS 09940 can be accomplished.

(3) Candidate systems. Candidate coating systems for new steel are recent technological developments in formulations of epoxies, such as epoxy novalacs and 100 percent solid epoxies. Additionally, 100 percent solid versions of polyurethane coatings are rapidly gaining recognition. Unfortunately, as with some new technologies, specialized methods of application are necessary. The 100 percent solid coatings often require complex plural component spray equipment. Therefore, skilled applicators are essential when using these systems. Industry-wide use of these systems will become prevalent as more restrictive VOC limits are enacted.

(4) Special concerns and cautions. Special concerns and cautions with existing systems are straightforward. The coating systems listed in CWGS 09940 for "Immersion and Frequent Wetting—Fresh (Inland Waters) or Prolonged Wetting by Splash, Spray, or Condensation" all require a high degree of surface preparation, generally, a minimum of abrasive blast cleaning per SSPC-SP 5. Because high performance systems are generally spray applied, highly skilled applicators are required, particularly on detailed and intricate structures. Vinyls are solvent deposited so they are easily cleaned and softened by higher solvent strength aromatic hydrocarbons and ketones, such as methyl ethyl ketone (MEK). Properties such as ease of cleaning and resoftening with solvent allow vinyls to be easier recoated and provide good bonding between cleaned coats. Also vinyls, as a result of their curing mechanism, often can be applied at much cooler temperatures. Unfortunately, the manufacture of VOC-complaint formulations of vinyls is progressing rather slowly, and the future use of these coatings may become more restricted.

(a) CTEs provide exceptional performance but are inherently difficult to apply. Because of their exceptional hardness, they are prone to intercoat delamination problems if critical recoat times are not observed. When overcoating for maintenance purposes, CTEs can present special surface preparation difficulties. When overcoating is required, the manufacturer should be contacted for special surface preparation requirements. Generally, the minimum requirement would be brush-off blast cleaning.

(b) Zinc-rich epoxy and zinc-rich vinyl coatings, in addition to being somewhat difficult to apply, require constant agitation to prevent heavy metallic zinc particles from falling out of suspension in the container. If not properly agitated, the resultant spray-applied film will not be homogeneous in regard to proper zinc particle distribution throughout the dry film. Consequently, the galvanic protection properties of the zinc coating are inhibited.

e. Painting of penstocks, spiral cases, spiral case extensions, and draft tube liners.

(1) Interior water contacting surfaces.

(a) Preferred systems. Of the existing systems listed in CWGS 09940 for painting penstocks, spiral cases, spiral case extensions, and draft tube liners, CWGS 09940 system 6, based on CTE, has provided a good history of corrosion protection and would be considered the preferred coating option. CWGS 09940 vinyl systems of the 4, 5, and 6 series have also proven successful when painting penstocks, spiral cases, spiral case extension, and draft tube liners.

(b) Special concerns/cautions. The curing mechanism of CTE is temperature dependent. Therefore, cool (surface, material, ambient temperatures $<10^{\circ}\text{C}$ (50°F)) temperatures would slow the curing/reaction process and could negatively impact construction scheduling. Conversely, vinyls, such as the 4, 5, and 6 series, cure by the mechanism of solvent evaporation, which permits application and curing. Where there is severe abrasion or high water velocities with large amounts of suspended abrasive matter (debris, ice, etc.), vinyls provide comparable performance to CTEs, but with the added flexibility of application at lower temperatures and fast dry/cure.

(2) Exterior surfaces of penstocks and appurtenances.

(a) Preferred system. Because of variable exposures of items on the exterior surfaces of penstocks and appurtenances ranging from outside weathering surfaces of penstocks to penstocks in humid tunnels, various systems are needed to adequately protect exterior surfaces of penstocks and appurtenances. Because there may be considerable variability in exposures, it is necessary to choose a system that will perform in the most severe exposure (high humidity and condensating moisture). Therefore, CWGS 09940, system 3 (vinyl) is the preferred system of corrosion protection. Also, because vinyls dry rapidly by solvent evaporation, they are more readily adaptable to the difficult drying condition encountered on exterior surfaces of penstocks and appurtenances than other generic types, such as epoxy or CTE.

(b) Dehumidification equipment. Particularly in summer months, condensating moisture and humidity present difficult problems in the coating of penstocks. Warm, moisture-laden air passing through the cool air naturally causes condensating moisture on the surfaces. Dehumidification equipment will be necessary to create ambient conditions more favorable to coatings application.

(c) Special concerns and cautions. In repair, replacement, or new construction of penstocks, hydrostatic pressure testing usually is required prior to placing the system in service. Testing requires that certain weld seams remain uncoated until testing is complete. Field touchup of welds may leave the structure with an aesthetically displeasing patchwork appearance, and adjacent coating may be damaged in the repair process. Therefore, USACE prefers to prepare and coat penstocks completely in the field. Unfortunately, field painting of completed penstocks presents particular health, fire, and explosion hazards, which must be carefully controlled with properly engineered ventilation systems (see Chapter 10). Special concerns with spent abrasive recovery, handling, and disposal also must be addressed.

f. Surge tanks.

(1) Interior surfaces of surge tanks. Surge tank interiors are well protected by using CWGS 09940 vinyl systems (3, 4, and 5 series) and CTE system (system 6). When painting surge tank interiors, mixed exposure conditions necessitate coating systems formidable to the exposure. Although there appears to be no clear preference for CTE or vinyl, a case-by-case consideration can aid in system selection. For economic reasons and simplicity, it is advisable to coat the surge tank surfaces with the same system as used in the penstocks.

(2) Exterior surfaces of surge tanks.

(a) Exterior surge tank surfaces can be effectively protected with CWGS 09940 system 2, linseed oil and alkyd primer/phenolic aluminum or system 3, vinyl, with the determining factor being the actual exposure.

(b) Special concerns and cautions are necessary when painting surge tank exteriors. As with many other USACE components, normal weathering predisposes the use of system 2 when climatic conditions or reservoir temperatures produce frequent wetting or prolonged periods of condensating moisture. Under such conditions, vinyl (system 3) should be used. Surface preparation would be sandblasting as outlined in CWGS 09940. If the exposure environment is not clearly defined, the vinyl system, which exhibits good resistance to both exposures (normal weathering or high moisture), should be used.

g. Crest gates.

(1) Existing exposures on crest gates may range from normal weathering exposure to areas of immersion and frequent wetting. Exposures such as immersion and frequent wetting are best protected using CWGS 09940 system 3, 4, or 5. Normal weathering exposure areas of crest gates would be well protected using CWGS 09940 systems 1 and 2 for steel in normal atmospheric exposures.

(2) Special cautions/concerns in coating crest gates may include variable exposure environments impacting on crest gates and depending on whether the painting surfaces are exposed upstream or downstream. The upstream side usually will receive the most severe exposure (immersion, abrasion, etc.). However, depending on certain conditions such as high tailwaters, downstream surfaces also may experience rather harsh exposures. Therefore, the most long-term, cost-effective method of coating would be the exclusive use of CW 09440 system 3 (vinyl with aluminum topcoats); or, if superior abrasion and mar resistance to debris and/or seasonal ice is desirable, use CWGS 09940 vinyl system 4 or 5 series.

h. Control gates and valves of reservoir outlet works.

(1) Preferred systems. Existing coatings listed in CWGS 09940 for control gates and valves of reservoir outlet works frequently are dependent on the level of exposure. CWGS 09940 systems 3, 4, 5, and 6 series, vinyls, and CTE are viable choices. Special attention should be given to the following concerns and cautions when specifying a coating system.

(2) Special concerns and cautions.

(a) Coating selection may vary considerably from project to project, depending on the following variables. Whether the water control device is operated fully opened or partially opened is important. If operated fully opened, whether the component is removed from the flowing stream of water should be noted; the component may be exposed to various degrees of abrasive ice- and/or debris-filled, fast-moving, turbulent water. If operated in the partially closed position or if exposed to flowing water, the severity of erosion and abrasion would be magnified. Additionally, the elevation and other characteristics of the service inlet may permit abrasives (ice, debris suspended matter, etc.) to adversely impact the system's service life. With this in mind, the following coating recommendations should be carefully considered. Structures in low-to-moderate water velocities (45.7 to 61.0 mm/sec [15 to 20 ft/sec]) with abrasive qualities are good candidates for coating with CWGS 09940 system 4 or 5 series or CTE. However, if extremely severe conditions can exist, neither of these systems are advisable,

and one of the specially reinforced systems (see Chapter 4) may be appropriate. Many types of gates (slide gates, tainter gates, tractor gates, fixed wheel, etc.) can be painted without difficulty; however, special attention is required when painting tractor gates. Specifically, the stainless steel roller chain and track assembly must be carefully protected during field painting. While in the erection phase, the roller chain most likely will not be installed, the stainless steel track will be bolted to the gate. Care must be taken to mask off or otherwise protect these track surfaces properly from blast damage, and to seal off bearings and other rubbing surfaces from abrasive blast particles.

(b) As previously discussed in this chapter and Chapter 2, a strong potential for galvanic corrosion can be set up by the coupling of dissimilar metals, such as stainless steel roller chains and tracks with tractor gate carbon steel surfaces. Therefore, a cathodic protection (CP) system frequently is used for enhanced corrosion prevention of the carbon steel surfaces on these gates. The specified coating must exhibit high dielectric strength, in addition to being carefully applied to avoid holidays. In this regard (high dielectric strengths), the use of CTE is superior to vinyl systems and is recommended for use on control gates and valves of reservoir outlet works in conjunction with a CP system. Discussions of total field painting procedures revealed that fewer holidays are noted when surface preparation and painting are done entirely after erection in the field. Therefore, these gates should be totally field painted with CP systems attached. Alternatively, total shop painting with CTE and attaching CP anodes prior to installation, with no field touchup, also has proven to be effective and economical. Also, CP is particularly effective in protecting bare steel exposed as a result of damage from impact or abrasion which may occur while the structure is in service.

(c) If the foregoing preferred options are not possible, careful consideration of the difficulties with recoating CTEs should be addressed. Specialized surface preparations, such as brush blasting, will be required if critical recoating times are exceeded.

(d) Hydraulic lines on control gates and valves of reservoir outlet works also present unique coating problems, particularly if they are immersed in water because hydraulic lines are vulnerable to exposure damage (from ice, debris, etc.). These hydraulic lines should be isolated with dielectric coupling and cathodically protected.

i. Trashracks for water intakes.

(1) CWGS 09940 systems 4 and 5 series (vinyl) with zinc-rich primers provide the best protection to difficult-to-

coat trashracks. From a design standpoint, trashracks present numerous coating difficulties, such as sharp edges. Because of their design and the fact that they are subject to flowing water with abrasive debris, seasonal ice, and mechanical raking damage, coating service life typically is shortened. Therefore, trashracks may best be left uncoated, with the possible exception of those in environments of severe corrosivity. If these items are coated, a periodic structural integrity inspection program is highly recommended. Oftentimes, it is more cost effective and easier to fabricate new racks than to attempt to refurbish existing ones.

(2) Special concerns/cautions when coating these items are straightforward. When the abrasive gouging action of ice is present, systems 4 and 5 series (vinyl) perform well; the zinc-rich primer systems provide the best performance. If the outage period is short or the weather is cool, the faster dry, low-application-temperature ($>2^{\circ}\text{C}$ (35°F)) vinyl systems would be appropriate coating choices.

j. Navigation lock gates, valves, and miscellaneous submerged metal. Lock gates and valves are well protected in this exposure using CWGS 09940 vinyl (systems 4 and 5 series) and CTE (system 6). The massive lockwall armor and protection angles are not critical to basic project functioning. Painting on construction (CWGS 09940 system 2) and possibly periodic maintenance for aesthetic purposes appears to be practical.

k. Navigation dam gates.

(1) Systems in existence are CWGS 09940, vinyl systems 4 and 5.

(2) Special concerns and cautions in painting navigation dam gates involve exposures unique to the structure. Gates are generally of the roller, tainter, or vertical-lift type. The exposure environment is that of turbulent water, physically trapped abrasive debris, drift materials, and seasonal ice. The abrasion-resistant qualities of system 4 or 5 generally are thought sufficient to provide good protection. However, in extreme conditions, metallized systems (see Chapter 4) should be considered. Roller and tainter gates have interior and exterior surfaces that require painting. Because grating protects the interior from abrasion, CWGS 09940 system 3 will provide adequate protection. Vinyls are high in solvent fumes and highly flammable; therefore, special care (see Chapter 10) is required for ventilation systems when coating with vinyls.

l. Freshwater (including potable) tanks.

(1) Preferred systems. Existing systems for freshwater

tanks are CWGS 09940 vinyl system 3, 4, or 5 series.

(2) Special concerns and cautions.

(a) Potable water tank lining demands coating systems free of harmful toxic chemicals. Special regulations, such as those of the NSF, govern such coating systems. Vinyls, because of their inert qualities, readily lend themselves to immersion in freshwater (including potable) tanks. They are neither toxic nor physically harmful to the person who drinks water that has come in contact with these coatings.

(b) Abrasion action from ice movement is often a factor in colder climates. Systems 4 and 5 series should be used in lieu of the less abrasion-resistant system 3.

(c) In conjunction with cool water stored in a tank interior, condensating moisture frequently is found on the exterior surfaces of the vessel. If this condensation becomes commonplace, the use of CWGS 09940 system 3 on the exterior surface is advisable.

m. Equipment for local protection projects. The equipment for local protection projects (slide gates, flap gates, etc.) and the portion of pumping units below the pumping station operating floor should be painted with a cold-applied coal-tar paint system, system 7 from CWGS 09940. This system is used because the manufacturers of the equipment involved are not prepared to thoroughly blast and apply the more costly and less user-friendly vinyl systems. Moreover, local flood-protection projects are given to local authorities, who are responsible for the maintenance of the completed project, and the maintenance of surfaces painted as advised here is more within their capabilities and experience. In essence, the recommended systems are more user-friendly and surface tolerant to the inexperienced applicator. Miscellaneous items of fabricated steel should be hot-dip galvanized after fabrication. Specifications for pump discharge lines are given in EM 1110-2-3105; they are to be coated on the inside with hot-applied, coal-tar enamel; however, this procedure is difficult in coating operations in small diameter piping. If the lines are buried in soil, the outside of the lines must be coated with hot enamel plus a felt wrap, which is applied in the shop in accordance with the American Waterworks Association (AWWA) Standard C203-91. The CTE, CWGS 09940 system 6 or 6AZ, also would be highly effective on discharge lines but it is not routinely available as a shop-applied coating.

n. Floating plant (steel construction) operating in fresh water. Varying surfaces and exposure environments are associated with the painting of a floating plant. Although this in itself is not unique, the additional color scheme

regulations imposed by ER 1125-2-303 often require the specifier to employ some alternative system combinations. Federal Color Standard 595 is used to dictate many of the color schemes for floating plants. Certain of the smaller crafts, such as skiffs, rowboats, launches, small boats, barges, and scows, are exempt from color scheme requirements. The following paragraph addresses coating application to the component.

o. Exterior surfaces of steel hulls.

(1) Certain modifications of CWGS 09940 vinyl systems 4 and 5 can acceptably accomplish coating of the entire hull. When special color concerns as identified in CWGS 09940 are necessary, such as hull surfaces above the waterline, substituting the last two spray coats of vinyl system 4 or 5 and/or substituting two black vinyl coats per V-103 is appropriate to achieve the special color. Also two final coats of Fed. Spec. TT-E-489 (black alkyd) may be used to achieve the special color.

(2) A garnet-reinforced system has been used for hull bottoms because frequent running aground results in severe abrasion and gouging of the coating system. Additionally, abrasion protection can be achieved by first priming the hull bottom with 2 to 3 mil of vinyl zinc-rich primer VZ-108, and following with the garnet-reinforced coating.

p. Interior surfaces of steel hulls. Hull interiors are subject to accumulating water, condensating moisture, and high humidity. Like other exposures of this type, these surfaces are well protected using CWGS 09940 systems 3, 4, 5, and 6 series. However, these systems necessitate sandblasting and may prove costly. A less expensive alternative would be to use a cold-applied, solvent-based coal tar (MIL-C-18480A(3)) in a two-to-three coat application. The saving is realized because of the lesser degree of surface preparation required by the manufacturer and the overall material costs. If the hulls remain dry, there are many less expensive systems, such as alkyd primers/alkyd topcoats, that can be applied over lesser degrees of surface preparation (i.e., SSPC-SP 3).

q. Painting of steel decks.

(1) Steel decks, if painted, are prescribed by the referenced regulation to be deck red, color 10076 of Federal Standard No. 595. The color requirement is waived when special, approved types of deck coatings are to be used. Red deck paint (Mil. Spec. DOD-E-18210B), three coats, is intended primarily for use on interior decks of naval vessels. It is based on a durable alkyd-phenolic-type of vehicle and is considered suitable for either interior or exterior use on floating plants operating in fresh water. This type of paint

should be used only on well prepared surfaces that are sandblasted to a commercial or better grade. Sand reinforcement of the second coat would be desirable when a nonskid surface is needed. Substitution of an inhibitive-type primer instead of the first coat of deck paint might be beneficial to the three-coat Mil. Spec. DOD-E-18210B system, but it is not considered essential for plants operating in fresh waters.

(2) Vinyl paint system from the 5 series having the V-106 topcoat from CWGS 09940 is the correct finish color and will perform well as a deck paint, although it would be somewhat difficult to sand-reinforce for antiskid purposes because of its fast-drying characteristics. The addition of fine garnet directly to the finish coats of this system will provide added abrasion resistance but minimal benefit in improved antiskid properties.

r. Exterior surfaces of floating plant.

(1) The color scheme for the painting of floating plant surfaces is prescribed in ER 1125-2-303. The surfaces involved are subject only to atmospheric exposure; although beneficial, blast cleaning may not be justified. If wire brushing and scraping (per SSPC-SP 2) are used, the surfaces will have corrosion products and mill scale present. One or two coats of a primer with good wetting properties, such as an alkyd rust-inhibitive primer, is advisable. Primed surfaces then could be finish coated with two coats of a semigloss enamel conforming to Fed. Spec. TT-E-529 (2) Class A. Enamel conforming to Fed. Spec. TT-E-489 Class A, or TT-V-1593 (silicone alkyd) should be used if a high gloss finished surface is desired. Both of these specifications include a range of gray, ivory, black, and red from which those suited to the floating plant color scheme may be selected. The finish coat enamels are relatively fast-drying materials and should not be applied to surfaces primed with slow-drying, alkyd primers without proper drying times.

(2) If an upgraded system is desired, the surfaces subject to atmospheric exposure could be cleaned by blasting to at least the commercial grade, and one or two coats of an alkyd rust-inhibitive primer should be applied. Finish coats of enamel conforming to Fed. Spec. TT-E-489 or TT-E-529 then could be used to comply with the required color scheme.

(3) Stacks of floating plants are required to be painted black with trim colors of red and aluminum. The use of special paints for these surfaces is determined by their maximum operating temperatures. Ordinary alkyd black paints, such as those included in Fed. Spec. TT-E-489 or

TT-E-529, will tolerate temperatures of up to about 135 °C (275 °F) for extended periods, as would an aluminum paint made with an alkyd vehicle (Fed. Spec. TT-V-109). Black paints (Fed. Spec. TT-E-496) will withstand temperatures of up to 204 °C (400 °F). For temperatures higher than 204 °C (400 °F), paints made with silicone or modified silicone binders must be specified. Fed. Spec. TT-P-28 covers a modified silicone-aluminum paint with a heat-resisting capability to temperatures up to 649 °C (1200 °F). MIL-P-14105C formulated products will resist temperatures as high as 760 °C (1400 °F) and are available in some colors. However, these products are expensive and frequently are available on a special order basis only.

5.6. Coating System Selection for Ferrous Surfaces in Seawater

a. Ferrous metal surfaces of fixed structures.

(1) Current systems. Current systems found in CWGS 09940 are:

- CTE (two to three coats).
- Epoxy zinc-rich primer/CTE (two coats).
- Epoxy polyamide (two to three coats).
- Epoxy zinc-rich primer (two coats)/epoxy polyamide (two to four coats).

Other existing systems (not listed in CWGS 09940), which have performed well, are formulations of coal tars, asphalts, Neoprenes™, and organic zinc-riches.

(2) Candidate maintenance systems. Maintenance painting, such as spot touchup, frequently is required to repair small failings or damaged areas on a structure. This process further lengthens the service life of a structure with an otherwise intact coating system. These maintenance repairs may be made to structures that cannot be taken out of service. Proper spot repair can permit the structure to remain in service until a time that is feasible to shut down for complete maintenance repainting. Surface preparation techniques are limited and generally are on the order of SSPC-SP 2 or SSPC-SP 3. Viable candidates for nonpermanent repairs are solvent-based coal tars and surface tolerant two-part immersion-grade epoxy mastic coatings. Keep in mind that these repairs are considered only temporary to preserve the structure until the time proper blast cleaning and recoating can be accomplished.

(3) Candidate systems for new steel. Candidate coating systems for new steel are recent technological developments in formulations of epoxies, such as epoxy novalacs and 100 percent solids epoxies. Additionally, 100 percent

solid versions of polyurethane coatings are rapidly gaining recognition, and inorganic zinc-rich coatings topcoated with organic paints also have performed well. Specialized methods of application may be necessary and most commonly require complex plural component spray equipment. Therefore, skilled applicators are essential when using these 100 percent solid epoxy and polyurethane systems. Industry-wide use of these systems will become prevalent as more restrictive VOC limits are enacted at the Federal, state, and local level. Contemplated systems must all be evaluated individually and specifically in this seawater immersion environment.

(4) Special concerns and cautions. Special concerns and cautions for immersion service in seawater were discussed in paragraphs 5-2a(3) and 5-4d. Additionally, the coating systems listed in CWGS 09940 for exposure to seawater all require a high degree of surface preparation—abrasive blast cleaning to white metal.

b. Steel piling.

(1) Existing CWGS 09940 CTE systems for coating steel piling are systems 6 and 6AZ (CTE). Systems 6 and 6AZ are suitable for protection of steel pilings. However, there are many questions about steel piling painting.

(2) Special concerns and cautions associated with the coating of steel pilings include the fact that no method of corrosion protection is used on certain portions of steel piling. Studies have shown that the corrosion rates of piling driven into undisturbed soil on the ocean floor corroded at slow rates mainly because of the lack of oxygen. Obviously, as the pilings emerge from the ocean mud floor, the presence of oxygen and consequent corrosivity increases. Moving soils, basic saltwater immersion, tidal movement, abrasives, contaminated waters, and aerated splash zone activity rapidly accelerate corrosive forces.

(a) The installation of pilings by driving them into the sea floor is believed to be particularly abrasive to a coating system. Initially, it was not known whether a coating system could withstand this installation without irreparable damage. However, it has been demonstrated that, when properly coated with CTE coatings, damage is limited to a few inches on the leading edge of the piling and relatively minor scratching in the interlock area. The addition of proper CP can protect these areas from corrosion.

(b) Interlock areas on sheet piling present some unique surface preparation coating difficulties, particularly the grooved areas. Even the best applied coatings to these interlock areas were believed to be damaged in the driving installation process. However, the damage is not as severe

as originally believed. In addition, this is the thickest part of the piling, and corrosion will have little effect on structural integrity. A suggested remedial action is to minimize corrosion through the use of galvanically protecting zinc-rich primer and periodically monitoring the corrosion rate and structural integrity. Experience has shown that, although corrosion will occur, it usually is of a localized nature and not critically harmful to structural integrity. However, corrosivity can vary from site to site, and periodic monitoring is considered vital.

(c) In cool environments, the temperature-dependent cure times of CTE and scheduled coatings operations (in shop and/or field) must be observed. Because exposure environments of pilings may vary (i.e., buried, immersion, splash zone), it seems proper to coat the pilings as outlined here.

(d) Underground portions of steel piling, which are a moderate distance below the groundwater table (or below the water-mud line if driven through surface water) do not seriously corrode. Therefore, the coating system may not be necessary 5 to 10 ft below these indicated levels. Sections of pilings subject to weathering and aerated splash zone activity would also be adequately protected using CWGS 09940 system 6 or 6AZ.

c. Cathodic protection (CP) and immersion in seawater.

(1) Certain inherent characteristics of seawater make it of greater corrosivity than fresh water. Because of this heightened corrosive nature, the use of CP in conjunction with immersion coating systems frequently is used for structures in seawater.

(2) High dielectric strengths, or the ability of the coating to withstand the additional stresses of the CP current is extremely important. Because the CP current forces water through the film in a process called endoelectrosmosis, a coating that can withstand this stress, such as CTE, is an important choice in conjunction with CP-induced stresses, of cathodically produced hydrogen gas and alkalis that are generated at the paint-metal interface. The desirable coating quality of high dielectric strength essentially forces the CP current along the painted film to breaks or discontinuities in the coating where it is needed for protection of the bare steel substrate. When choosing a CP system for a structure that is partially seawater immersed and partially atmospherically exposed in the splash zone, CP may not provide adequate protection to the splash zone portion. The highly oxygenated splash zone is severely corrosive and requires higher CP rates that could be detrimental to the submerged CP-protected areas. Additionally, coating choices must be resistant to these forces when used with CP.

5-7. Coating System for Iron and Steel Pipe

a. *Black iron or steel pipe.* Existing systems for coating black iron and steel pipe are alkyd inhibitive primers, with ready-mixed aluminum and alkyd topcoats. CWGS 09940 also specifies the use of vinyl systems in some exposures. A clear, varnish-like coating sometimes is present on black and steel pipe. In nonsevere exposures, the coating generally is compatible with alkyd coating systems. Solvent cleaning and hand-tool cleaning generally are adequate for coating with alkyd systems. However, if the exposure environment becomes more severe, a corresponding upgrade in surface preparation and coating choices, such as a vinyl (CWGS 09940 system 3), is appropriate. The required spray application of vinyl on piping in place can prove to be labor intensive. Upgraded surface preparation and protection with additional coats of alkyd or phenolic topcoats may prove to be a viable alternative.

b. *Galvanized pipe.*

(1) Coating systems for galvanized pipe are generally for appearance purposes or for the refurbishing of damaged galvanized components. Zinc-rich epoxy polyamides and

coatings specially formulated for galvanization are useful in this regard. The zinc-rich coatings are abrasion, chemical, and moisture resistant. Consequently, they frequently are used without a topcoat, even in severe exposures. Adhesion to this substrate may be variable because of the galvanizing process, and care must be taken in the surface preparation process to assure that all galvanizing process oils are totally removed before painting. This normally can be accomplished by solvent or detergent cleaning.

(2) Threading and welding of galvanized pipe after production leave exposed steel, which requires touchup. Epoxy zinc-rich primer coatings are extremely effective in this regard. These coatings have good adhesion qualities to existing galvanized surfaces and, in themselves, provide similar galvanic protection to the touchup areas.

(3) Thinly applied vinyl wash coats (0.0076 to 0.013 mm [0.3 to 0.5 mil] dry film thickness [DFT]) also have proven to be an effective tie coat on galvanized pipe that provides a sound base coating for high performance barrier-type topcoats. Primarily though, these systems are used only in frequent condensation and moderate corrosivity, when the galvanization itself may readily react and rapidly deteriorate by galvanic action.

Chapter 6 Maintenance Painting

6-1. Introduction

Maintenance painting of USACE structures provides an economical means for preventing corrosion and metal loss. This chapter explores the purpose of maintenance painting, provides details on conducting maintenance painting surveys, and details three approaches to maintenance planning.

a. Design problems. The design of a structure is generally centered on performance first, then longevity and efficiency. Only after those criteria are met is aesthetics considered. Because of this hierarchy, a successful structural design may present difficulties with the application of protective coatings. Back-to-back angles, sharp edges, and inaccessible areas restrict the coatings' ability to flow and provide coverage of the substrate. The use of dissimilar metals in design without regard to corrosion protection can result in extensive and costly repairs. Insufficient drain holes, which subject coatings designed for atmospheric exposure to an immersion service environment, subsequently cause failure. All design mistakes hinder the successful coating application and hence the performance, longevity, and ultimate efficiency of the structure and/or process.

b. Purpose of maintenance program. There are six reasons to properly develop, implement, and maintain a maintenance painting program: facility upkeep, corrosion protection, aesthetics, cost savings, energy conservation, and safety/identification. These factors all enter into the maintenance painting decision-making process.

(1) Facility upkeep. Facility upkeep is an all-encompassing concept. How smooth or well an operation functions can be a direct result of management's commitment to both the long- and short-term benefits of continual surveillance and remediation of corrosion. When the owner provides for continued maintenance, unscheduled shutdowns because of equipment and/or structural corrosion-related failures can be avoided. The rehabilitation of the facility then can be maintained through planned downtimes and/or scheduled preventative maintenance procedures.

(2) Corrosion protection. Corrosion protection, combined with loss of structural integrity, is generally the overriding and primary purpose of a maintenance painting program. When properly designed and maintained, major and costly procedures (complete removal and replacement) can be avoided. The location of corrosion may identify

poor coating system selections and areas of poor design and construction. By designing a maintenance painting program strictly around corrosion, the results lend themselves to the identification and prevention of all other factors mentioned: operations, aesthetics, savings, conservation, and safety-related factors.

(3) Aesthetics. Aesthetic concerns vary considerably, depending on the specific industry. For example, manufacturing or fabricating facilities generally do not adopt or assign the same weight or importance to aesthetics as would those in the food industry. Accordingly, the appearance of a lock and dam is important because it is public property. It is visited by the public and represents the use of tax dollars. Tourist attraction areas may be more important aesthetically than some remote storage area. The degree of importance placed on aesthetics will have an effect on the frequency of painting, type of coating materials used, and color selection. If aesthetics is a motivating factor in a maintenance painting program, coating characteristics such as fading, chalking, checking, and rust stains will enter into the decision.

(4) Cost savings. Cost savings can be achieved if the maintenance program is designed so defects, such as corrosion, aesthetics, etc., are identified prior to the need for extensive surface preparation and recoating work. The life cycle cost of a coating is lessened considerably when regularly scheduled periodic repairs are performed.

(5) Energy conservation. Energy conservation also may be a consideration in specialized instances within a facility. Color selection is the key factor when energy conservation becomes a component or requirement within a program. An example of this would be the selection of a dark-colored coating on the exterior of a water storage tank. The increased heat generated on the interior may be sufficient to eliminate the formation of ice in the winter months and/or assist in some chemical reaction in a later process. If the structure is heated, the use of a light color could reduce the potential hazards with flammable and/or combustible material.

(6) Safety/identification. Safety/identification can be factors in a maintenance painting program if protection of employees and/or visitors is a predominant concern in a particular area or process. The Federal Aviation Administration (FAA) requires a checkerboard pattern on water storage tanks, radio towers, and other high structures near airports. Color-coded piping systems and nonskid deck coatings also are examples of color-coded material selection that enhances safety. First aid stations and fire extinguishers are commonly identified and located at a facility by color identification.

6-2. SSPC Paint Guide 5

The Steel Structures Painting Council (SSPC) Paint Application Guide No. 5, "Guide to Maintenance Painting Programs," provides procedures for planning and carrying out a maintenance painting program. This guide recommends that programs define the purpose of maintenance painting (corrosion protection, appearance, safety or identification, and energy conservation), consider the timing of the project (for example, short- or long-term painting program in time to schedule shutdowns), and recognize the economic issues and the need for environmental protection during the work.

6-3. Conducting Maintenance Painting Survey

a. Survey types. A brief summary of the types of surveys that can be undertaken to establish a maintenance painting program follows.

(1) Minimal walk-through survey. A minimal walk-through survey involves a subjective visual assessment of the overall condition of the coatings within a given area of the facility (lock, dam, public use area). The coatings within the areas are rated according to the painting needs of high, medium, or low priority, or some other qualitative rating scheme such as no coating work required, touchup only, or complete removal. When using a priority grading scheme, corrosion, process, contamination, safety, etc. all may be utilized as criteria. It may be helpful to conduct a quick walk-through of the facility to obtain an initial understanding of the range of coating conditions found throughout. This observation would provide a means of anticipating the amount of information to be gathered in the upcoming survey. If a wide range of conditions exist, more extensive testing may be required to determine the varying environments and causes of premature system failures. The initial walk-through provides an indication of the condition of the coatings and helps to establish a logical approach to organizing data collection.

(2) Midlevel survey. A midlevel survey will provide more information for planning maintenance painting than will the minimal survey. For a midlevel survey, drawings can be used to better divide the facility into well-defined areas. Within each area, painted items may be subdivided into categories such as structural steel, floors, tanks, piping, etc., rather than assessing the overall condition as a whole. This type of breakdown would provide a greater distinction between the items surveyed. An alternative would be to organize the items according to architectural, electrical, mechanical components, etc. An example would be to grade (examine) all structural items (walls, floors, ceilings) as architectural components under one grade, if all were in

the same condition. The deterioration of the coating is assessed quantitatively in terms of visible corrosion, peeling, blistering, flaking, etc. The percentages of defects can be determined in accordance with SSPC VIS 2 or other custom-designed rating schemes. Specific rating scales for blistering are found in ASTM D714. Chapter 9 discusses inspection procedures in detail.

(3) Detailed survey. The detailed survey divides the plant into areas but further identifies individual components. For example, electrical equipment is not examined as a whole. Instead, individual motors are assessed, as are control boxes, conduit, etc. In addition, physical tests of the coating thickness, adhesion, and examinations of the substrate beneath the film are made for the presence of mill scale, corrosion, or deterioration. The advantage of this level of detail is that decisions can be made about whether the existing coating is of sufficient strength and integrity to be repainted, or if it is unable to support the application of additional coats.

b. Survey data. Although surveys generally can be classified as discussed here, various combinations of survey data can be developed. For example, a simple visual survey that qualitatively assesses the painting needs as high, medium, or low priority can be supplemented by a few physical tests of the coating integrity to determine if the existing system can be repainted without risk of disbonding. The various survey techniques and information that should be considered when collecting field data are described below.

(1) Area location. The specific location of the portion of the structure being surveyed is identified.

(2) Painted items. A listing of the painted items is compiled. Items may be inventoried as the smallest common element (e.g., pipes, stairs, railings, pumps, and motors) or as general categories (e.g., tanks, structural steel, floors, piping, and supports), depending on the level of complexity of the survey. When the need is to collect only general overall coating condition data, little to no individual inventorying of items is necessary.

(3) Service environment. The service environment for the coating system is identified. The environment includes not only the general operating conditions but any potential extreme or upset conditions such as temperature spikes, splash, and spillage. The service environment information is necessary when selecting maintenance coating systems. The most common service environments encountered are: interior, exterior (rural, residential, and industrial), immersion (liquid), temperature, and abrasion resistance. Detailed information on coating selection is found in Chapter 5.

(4) Existing coating type. If the percentage of corrosion and the adhesion of the remaining intact coating provide for overcoating, the existing coating must be identified to enable the selection of a compatible material for maintenance painting. If the coating type is not known through historical records, samples can be removed and analyzed in a laboratory to determine the generic type. Alternatively, ASTM D5043 provides a series of tests that can be conducted in the field to obtain a general indication about the generic type. The specific procedures are discussed in Chapter 3.

(5) Physical tests of coating integrity. The existing adhesion within the paint system is important if any overcoating is recommended. It also comes into play when examining the test patch results of candidate repair systems.

(6) Coating thickness. The film thickness of the entire system, as well as the individual layers, is important. This information and the corresponding adhesion may determine the type, level, and degree of surface preparation required if overcoating is recommended. This testing can be performed nondestructively and destructively as described in Chapter 9.

(7) Substrate condition. The underlying substrate must be examined for the presence of underfilm corrosion, rust scale, mill scale, or deterioration typical of the substrate itself (e.g., underfilm rust and rusting mill scale). The coating can be removed from adhesion test sites by cutting and scraping to examine the substrate, or through the use of chemical strippers. Deterioration of the underlying substrate may influence repainting decisions.

6-4. Analyzing Survey Data

a. The interpretation of the survey data requires the ability to change field test results into meaningful information. The painting needs of the entire area should be examined, not just individual components. The unnecessary application of additional layers or coats of paint can ultimately be a deterrent to the performance of a component because the additional paint now makes the system thick and heavy and can cause cracking, peeling, and subsequent detachment. It may be desirable to delay the rehabilitation (painting) of a badly corroded item until other items in the surrounding area also require work. As a result, there would be a delay in repainting certain isolated surfaces that need repair, which is the case in most maintenance painting programs. The objective is to identify and schedule those areas for repainting that require only minimal surface preparation. Cost-effective maintenance typically can be achieved if the amount of deterioration is less than 3 to 10 percent of the surface. Beyond this

percentage, it may be more cost effective to allow the surface condition to continue to deteriorate and to schedule the items for total removal and replacement.

b. Common conditions analyzed to determine if an existing coating can be upgraded include: the extent of corrosion on the structure, the total thickness of the existing coating system (including the number of coating layers), the adhesion characteristics of the system, the condition of the underlying substrate, and the generic type of the existing system to ensure compatibility. Data needed to determine repairability of the coating include: visual assessment of the extent of corrosion and deterioration, flaking paint, physical tests of the coating thickness and adhesion, and an assessment of the substrate for mill scale and underfilm corrosion.

c. Not all coating systems are candidates for upgrading. For example, if the extent of deterioration is excessive, more surface preparation may be necessary than would be economically justifiable. The existing system may be of poor integrity and not strong enough to withstand the weight and stress imparted by the new system. Incompatibility between coating systems can result in softening and lifting of the existing system or poor adhesion to it. Any of these factors can result in cohesive and/or adhesive failure and increased costs because of needless or excessive system repair and replacement. Visual evaluations and physical testing are essential to prevent many of these, or similar, consequences.

6-5. Maintenance Painting Approaches

After the facility has been surveyed and the data analyzed to establish the high priority items for repainting, it is necessary to determine whether the coating should be touched up, touched up with a full overcoat, or completely removed and replaced. These maintenance options involve an assessment of both the overall percentage of coating deterioration and the physical attributes of the existing coating system. Total removal and replacement versus maintenance painting is typically considered when more than 3 to 10 percent of the coating has deteriorated. The wide range in percentages depends on the distribution of the corrosion across the surface. For example, a 3 percent coating failure distributed across an entire structure would be considered to be beyond the realm of touchup because, by the time each localized spot is properly prepared for repainting, a substantial amount of coating removal will have been necessary and there would be a significant number of overlap areas between the new material and the original system. Without extensive feathering of edges, each overlap can lead to a weakness in the total system, with lifting of edges and premature failure. When failure is

more localized, as much as 10 percent or more of the surface may show deteriorated coatings, yet still be a candidate for maintenance painting because of the localized nature of the defects.

a. Integrity of existing coating. In addition to the distribution and percentage of corrosion, maintenance painting options are strongly influenced by the integrity of the existing coating. The point at which a coating is beyond consideration for rehabilitation because of its thickness or adhesion or the presence of underlying rust or mill scale varies according to coating type, the severity of the environment, the method of preparation to be used, and the coating system to be applied.

(1) Adhesion. ASTM D3359 adhesion ratings of 0A to 1A (removal of coating from most of the area within the X to beyond the X) or 0B to 1B (detachment within the lattice pattern from 35 to 65 percent of the area and greater) for many coatings would be considered to be associated with a high risk in recoating. However, areas of poor adhesion such as this have been successfully topcoated. Conversely, adhesion ratings of 3A and better (removal only up to 0.003 mm [1/8 in.] on either side of the scribes) or 3B and better (removal within less than 35 percent of the lattice pattern), which would typically be considered to be adequate adhesion for repainting, have been observed to spall. A definitive criterion for coating strength has not been established for the tensile adhesion tests, although a minimum of 1,378 kPa (200 psi) has been specified in the nuclear industry for coatings specified to be used within primary containment according to the American National Standards Institute (ANSI) N5.12-1974. When determining the ability to repaint a system based on adhesion, the tensile tests and knife tests may provide conflicting results. Industry professionals believe that adhesion testing, in general, is not a reliable predictor of coating performance. For example, coating systems that exhibit poor adhesion test values do not always fail, and systems that exhibit adherent test results sometimes fail prematurely. Because definitive rules for adhesion cannot be provided, decisions may have to be based on experience and subjective probing in conjunction with ASTM D3359, Method A knife test.

(2) Coating thickness. Coating thickness also plays a role in determining whether maintenance painting is a viable option. There are no established rules to determine when a coating is too thick to be repainted. For example, a 0.127-mm- (5-mil-) thick film with poor adhesion would not be a candidate for repainting, but a 0.635-mm- (25-mil-) thick coating with good adhesion might be a candidate for repainting. However, with aged alkyd systems, when the thickness measures 0.635 mm (25 mils) or more, the surface typically has already been repainted a substantial number of

times, resulting in aged undercoats with poor cohesive and adhesive strength.

(3) Substrate condition assessment. The final assessment of the coating system that must be considered when determining repaintability is the presence of underlying mill scale or corrosion. The presence of mill scale or thin, tight corrosion is of less significance if the adhesion is good and the thickness is moderate. However, if the adhesion is suspect or poor, and/or the thickness is heavy, the presence of underfilm corrosion and mill scale becomes of greater importance. In many situations, it is not worthwhile to attempt the full overcoating of an old paint system of marginal integrity if mill scale and underfilm corrosion are present.

b. Hazardous material consideration. The presence of paints containing hazardous materials such as lead or chromate also can influence coating repair versus removal decisions. Under the Interim Final Rule on lead in construction, the presence of any lead in the existing coating, regardless of the amount, requires specific measures for employee protection. Small amounts of lead in vinyl paint and zinc-rich primer have been found. Although painting items with these systems is not normally considered to be a lead removal project, the OSHA requirements apply. The costs associated with the removal of lead paint can be extremely high because of the need for containment of the debris, the possible need for environmental monitoring of emissions, specialized worker protection requirements, and the controls needed for the handling and disposal of hazardous waste. Therefore, when assessing coating repair versus removal options, the cost associated with lead paint removal may make system touchup or touchup and overcoating to extend the life of the system a desirable alternative. Kline and Corbett (1992) discuss extending the life of an existing system, primarily a lead-based paint system. This chapter (paragraph 6-10) discusses these issues of maintenance painting in detail.

c. Maintenance painting options. Maintenance painting options are based on the amount of coating deterioration present and the physical integrity of the existing system. A discussion of the options follows.

(1) Spot repair (touchup) only.

(a) When only a few localized failures are occurring, or the integrity of the coating is such that it will not withstand the application of a full finish coat, localized spot repairs should be considered. However, spot repairs can be aesthetically unpleasing. If aesthetics permits, the spot repairs typically will be done economically to extend the life of the system and without risking wholesale detachment

from the stresses imparted by application of full cosmetic coats. The selection of the surface preparation method is just as critical as coating selection. If the existing system is extremely brittle, the use of any abrasive blasting procedure may damage adjacent areas, thus creating a larger area of potential detachment and failure. The use of power tools offering a more controlled work area may be better suited to small, isolated repairs.

(b) Compatible systems must be selected to assure that there is no lifting at the overlap of the painted area. If the surrounding coating is painted at the same time, it must possess adequate strength and integrity to withstand lifting or disbonding from the application of the additional coats.

(c) The selection of upgraded coating systems should focus on materials with low shrinkage characteristics during curing and high solids content to minimize solvent penetration and softening of the underlying system. Because many upgrade projects involve large exterior structures subject to varying degrees of corrosive environments, the selection criteria also should include a substantial measure of resistance to atmospheric exposure and appearance.

(2) Spot repair (touchup) and full overcoating. Spot repair or full overcoating are the most traditional approaches to maintenance painting when the coating system can withstand the application of additional coats. Localized areas are spot repaired then a full overcoating is applied to the entire surface. A full coat is applied to correct localized pinpoint deficiencies that may not be visible during inspection or that may not be feasible for a one-for-one repair. Also, the longevity of the coating system typically is improved considerably through the application of a full overcoat.

(3) Complete removal and replacement. In a well-engineered maintenance painting program, the need for total removal and replacement of the coating system is minimized considerably. Coatings are repaired before the deterioration progresses to the point at which total removal and replacement is the only option. When a maintenance painting program is initiated, many areas of a structure may be in need of total coating removal and replacement. This is common when converting a facility to a properly engineered maintenance painting program.

d. Cathodic protection (CP). CP may be present and require an examination to ensure that it is performing as designed. This specialized field requires a properly trained professional. The periodic maintenance required with this form of corrosion protection, such as anode replacement, frequently is neglected. Candidate areas for installing CP may include areas that are difficult to prepare and paint or

that, when repaired, cause a disruption in service.

6-6. Application of Test Patches of Coating Materials

a. Test patch application and analysis should be accomplished in accordance with ASTM D5064. Test patches should be applied to representative areas of the structure and be permitted to cycle through a winter season to apply additional environmental stress to the coating. If the cycle cannot be extended, a minimum of a few weeks curing time should be allowed prior to visual inspection for lifting, wrinkling, or other signs of incompatibility, and for an assessment of coating adhesion.

b. When preparing a coating for a test patch, the surface preparation must be carefully selected and should be included in the test programs just described. For old, aged, deteriorated coatings, compliance with SSPC-SP 7 may be too severe and may fracture and weaken the existing film; additional coats may cause detachment of this damaged coating. Scrubbing the surface to remove chalk, grease, oil, and dirt may be the only procedures needed.

c. If a coating system has been identified as "upgradable," test patches of the candidate system(s) should be applied prior to committing to upgrading on a large structure. Coating test patches frequently are applied in accordance with ASTM D5064. This standard covers the procedures for field testing of coating compatibility when maintenance of an in-place coating system is being contemplated.

d. If the coating is thick (0.635 to 1.016 mm [25 to 40 mil] or more) and the system's adhesion is poor to marginal, any decision to attempt recoating will necessitate the application of test patches. If test patches are not feasible, an additional method for determining the repairability of a system is to expose the samples to accelerated weathering using one of the weathering chambers described in Chapter 3. After weathering, the samples can be examined for lifting, loss of adhesion, and other physical characteristics. Obviously, total removal is preferable if it is economically feasible. However, when total removal is not feasible, and if test patches are successful, even areas containing otherwise poorly adherent coatings could be candidates for upgrading.

6-7. Identification of Existing Coating as Containing Lead

The existence of lead in a coating must be identified prior to considering maintenance alternatives. There are several methods for identifying whether or not a coating contains

lead. Methods utilized for field determination include portable x-ray fluorescence (XRF) and chemical spot tests. Laboratory analysis of samples removed from the field is accomplished using atomic absorption spectroscopy (AAS) and inductive coupled plasma atomic emission spectrometry (ICP-AES).

a. X-Ray fluorescence.

(1) Portable XRF detectors are used directly on the painted surface to provide a nondestructive analysis of the amount of lead present. The lead in the coating is expressed as mass concentration per unit area in milligrams per square centimeter (mg/cm^2). The portable XRF detector utilizes a radioactive source (e.g., Co^{57}) and bombards the painted surface with x-rays that excite the lead atoms present. The intensity is measured by the detector and is related to the amount of lead in the coating. Although the testing of the paint film is considered to be nondestructive, the coating from representative substrate types must first be stripped to determine background values for each substrate. The readings obtained on the painted surfaces then are adjusted by subtracting the background values.

(2) Two types of portable XRFs are used: direct-reading and spectrum analyzers. The radioactive source in the detectors maintains its strength for approximately 1 year before replacement is required. The equipment costs range from \$8,000 to \$20,000 or more (1994 dollars), with the source replacement cost an additional \$1,800 to \$3,000 annually. Because of the radioactive source, the XRF operators must be trained by the equipment manufacturer and the owner licensed by the state in which the tests are performed. Therefore, it normally is not cost effective for an owner or contractor to purchase these machines for a few tests.

(3) Aside from the financial and licensing drawbacks, these XRF devices establish the lead content as a concentration over a given area; this is contrary to industrial paint evaluations for which the lead is expressed as a percent by weight. The influence of the steel substrate on the instrument reading also can affect the accuracy of the determination. Although the use of portable XRF detectors might provide an indication about whether or not lead is present on an industrial structure, no guidance is available on interpreting the results. As a result, it does not appear that portable XRF detection of lead in industrial paint will be used with any regularity in the near future.

b. Chemical spot tests. Careful use of spot tests may indicate that lead is present above a certain level, but the results are not quantitative. Also, the results can be misinterpreted: when lead is present but the color change

is not recognized, or when lead-free coats mask the lead-containing coats from the test. However, spot tests for conducting initial field surveys and in conjunction with fewer (and more expensive) confirmatory samples submitted for laboratory analysis allow for more efficient and cost-effective sampling procedures. At a minimum, confirmatory samples for representative negative determinations are required. It is also wise to confirm a few positive samples as well. Chemical spot tests involve the use of sodium sulfide or rhodizonate, which react with lead-based paint and produce notable color changes. The procedures describing their use follow.

(1) Sodium sulfide. Spot testing using sodium sulfide is a qualitative method for determining the presence of lead. One method of conducting the test involves cutting a beveled scribe through the coating down to the substrate, exposing each of the layers within the coating system. A 6 to 8 percent aqueous solution of sodium sulfide is deposited across the scribe, and a reaction occurs between lead and the sulfide ion to form black lead sulfide. The change to a gray/black color typically occurs within seconds. If the existing coating is white, or a light color, and only one or two layers, this test may provide a viable means for determining whether or not lead is present. However, industrial paints typically are many layers, only a few of which may contain lead. An adequate area of each layer must be exposed to make the visual determination of color change. Additionally, the interpretation of a color change may be difficult with darker coatings, particularly when only thin layers are exposed for testing. The tester also must be able to distinguish between the darkening of a layer of the coating that may occur from the wetting solution compared to a darkening caused by exposure to sodium sulfide.

(2) Rhodizonate. Another spot test relies on the reaction between lead and the rhodizonate ion to precipitate a pink complex. The coating film is cut or sanded away to the substrate to expose a cross-section of the film, and a solution of rhodizonate is directly applied using a special applicator or applied to a filter paper that is placed against the surface. The reaction, which may occur instantly or require a few minutes, creates a rose-red coloration that indicates the presence of lead.

c. Laboratory analysis. Lead can be quantitatively identified and measured when properly sampled and analyzed in the laboratory. The laboratory analysis of lead content typically is accomplished using AAS or ICP-AES testing methods. The AAS tests are conducted in accordance with ASTM D3335. Methods 7420 and 7421 of the USEPA Manual SW-846, address lead detection by using a flame method and a graphite method, respectively. Method 7420 has a detection limit of 0.1 milligram per liter

(mg/L) or parts per million (ppm). According to Method 7421, the detection limit using the graphite procedure is far greater at 1 microgram per liter ($\mu\text{g/L}$) or parts per billion (ppb). ICP-AES tests are conducted in accordance with Method 6010 (EPA SW-846).

d. Sampling procedures. Regardless of the laboratory method used for detecting lead, the samples selected for analysis must represent the range of coating thicknesses on the structure and the number of coats. The total thickness of the paint film must be removed cleanly to the substrate to ensure that the sample represents all of the coating within a well-defined area and that it is not diluted by a disproportionate amount of any coating layer. Controlling rust, mill scale, and other debris in the sample also is necessary to provide quality samples for laboratory analysis. The effects of undesirable materials in the sample will either invalidate the results because of the contaminants or increase the cost of the analysis because of the additional labor necessary to segregate the sample. Each sample should be submitted in a separate, sealed, and noncontaminated bag and identified with at least the project site, date, location from which the sample was taken, and name and signature of the sampler.

6-8. Impact of Costs of Lead Paint on Surface Preparation

In general, all activities associated with lead paint will be associated with high costs. Since the late 1980s and early 1990s, the industry has seen a significant increase in costs associated with concerns about lead and other hazardous materials. In response to these concerns, advances in the field of lead paint removal, primarily in the efficiency of containment/collection methods and the use of recyclable abrasives, have presented methods of cost control and enhanced worker and environmental protection. A major indirect cost of lead paint removal involving the concerns about the lead hazard includes environmental and worker protection, equipment, and labor.

a. Environmental and worker protection. A major indirect cost of lead paint removal involves the planning and engineering process necessary before commencing a project. The following discussion on the aspects of surface preparation costs affected by these lead hazard concerns includes environmental and worker protection, equipment, and labor. Chapter 11 specifically discusses these regulations. The factors affecting the regulation requirements include: worker protection and training, ventilation systems, air monitoring, and hazardous waste handling. Lead removal operations require enhanced levels of worker protection that add significantly to the costs of the project. Costs for compliance include new equipment (i.e.,

respirators), fit testing, training for each employee and supervisors, learning about and understanding regulations, additional paperwork to document compliance with OSHA and other standards, and increased insurance in some situations. There is a significant cost for the containment of the paint removal operations, for air and soil monitoring, and for disposal of the spent debris to ensure environmental protection. The largest cost item for full removal and repainting is containment and disposal; and it may be twice as expensive as when overcoating, but the projected coating life may be two to three times as long as overcoating. Cost increases because of environmental protection are difficult to accurately determine because compliance with nonstandardized requirements, which change regularly, depends to a large extent on the contractor's ingenuity and integrity.

b. Equipment. Equipment costs may be significantly higher when preparing surfaces containing lead paint. The factors affecting equipment costs include: initial investment or rental fees, removal effectiveness, quality of surface preparation, production rates, specific abrasives used, dust and debris generation, and containment required.

c. Labor. Labor costs invariably will be higher when maintaining a lead-based coating. Factors affecting labor costs include: production rate of the equipment used, extent of containment requirements, production losses caused by use of personal protection equipment, and training costs.

6-9. Maintenance Alternatives

Initial inspection of the existing coating system is necessary to determine the appropriate method of maintenance. No regulations require the removal of industrial lead paint; therefore, extending the life of an existing coating for 7 to 10 years through overcoating might provide a viable, cost-effective alternative for maintaining the structure. The cost of lead paint removal may or may not increase in the future and regulations may become more restrictive; however, prices may decrease because of the emergence of new technologies for lead paint removal and containment and as contractors gain more experience. Methods of maintaining a coating system containing lead include total removal and various techniques to upgrade the existing system. All maintenance alternatives for existing lead-containing coatings must comply with the worker protection requirements of the OSHA Construction Lead Standard (OSHA 6-9). Containment alternatives are discussed separately in this chapter.

a. Total coating removal and replacement. Total removal and replacement is the most costly alternative and

may require elaborate controls over containment, worker protection, environmental protection, and debris handling and disposal. However, this alternative will provide the greatest system longevity, totally eliminate the hazardous paint, and eliminate the possibility of escalating removal costs in the future.

b. Coating system upgrading. Upgrading a coating system refers to the application of an additional barrier coat to increase the protective life of the existing coating system. Techniques to achieve cost savings by system upgrading include: spot touchup, partial removal, and zone painting. The overall advantages of upgrading the existing system include: considerable cost savings over total removal, utilization of future advances in lead removal technology, and cost-effective maintenance of the structure. Regardless of the actual costs for total removal versus rehabilitation, upgrading will be considerably less expensive. However, not all coatings or service environments are candidates for this approach, and the possibility of upgrading the system must be determined. The amount of spot repair required to assess the upgrade and to allow the contractors to bid on an equal basis also must be assessed. Methods of determining the upgrade of an existing system are discussed earlier in this chapter.

(1) Spot touchup. Spot touchup has several advantages. A minimal amount of lead paint is removed, and a less aggressive method of preparation can be used (e.g., hand- or power-tool cleaning). The impact on environmental emissions and worker exposures is greatly reduced, the containment needs are minimized, and the volume of waste is reduced.

(2) Partial removal. Partial removal may minimize the amount of lead paint to be removed if there is a sound intermediate coat over the lead primer. This alternative may provide a more cost-effective means of extending the life of the existing system with minimal surface preparation, if the work is scheduled before an extensive amount of rusting is visible, and if the existing system is of adequate strength and integrity to be recreated. If the intermediate coat is not sound, or many scattered spots of rusting are present and require preparation, the repair may dislodge enough lead to require additional environmental and worker protection and reduce the advantage of this alternative.

(3) Zone painting. Zone painting can increase the life of an entire system without specifying complete coating removal and replacement over the entire structure. The advantage is that the entire coating system is not arbitrarily removed and replaced because of severe deterioration in only a few places. The lead removal concerns are restricted to well-defined areas, and the remaining surfaces are

overcoated at the same time.

6-10. Surface Preparation and Coating System Selection

a. Surface preparation alternatives. Surface preparation alternatives for a lead-containing paint coating are similar to typical preparation alternatives discussed in paragraph 6-5c. However, containment of the blast process is necessary because of potential overblast and hazardous debris concerns when preparing an existing lead-containing coating system. Abrasive spot blast cleaning will provide the best surface cleanliness and anchor profile necessary for many high performance coating systems, but it will generate the greatest amount of lead dust. However, if the existing topcoat is peeling but the underlying coatings basically are intact with minor pinpoint rusting, hand-tool cleaning (SSPC-SP 2) or power-tool cleaning (SSPC-SP 3) may be used to prepare the surfaces to minimize the generation of dust. The overall success of the repair depends highly on the quality of the surface preparation.

b. Coating system selection. The coating system selection process is similar to that of typical system selection methods. However, the added concern of further contamination from the remaining lead-containing coating must be addressed thoroughly prior to a final coating system selection. Compatibility between the existing coating and the candidate maintenance system is especially important, and test patches are strongly recommended.

6-11. Work Area Control Practices

After the ability to upgrade a system is determined and the alternative maintenance procedure is selected, work area practices must be established for control of lead exposure to the workers and to isolate hazards from surrounding operations and other personnel. Control practices should include precleaning of the work area, containment setup and isolation, establishment of a restricted area, and final cleanup. These practices are to be used when cutting, welding, or burning on surfaces coated with lead-based paint, or when hand-tool or power-tool cleaning, minimal blast cleaning, or chemical stripping processes are used for removal of lead-based paint on small area projects.

a. Precleaning. The precleaning procedure is used on all small area removal activities involving lead-containing paint coatings. Precleaning consists of vacuuming the immediate vicinity of the removal area within approximately 15 ft in all directions with a high efficiency particulate air filter (HEPA) vacuum to remove any existing debris or contamination.

b. Setup and isolation. Three methods of small work area setup and isolation are frequently used. The method selected depends on the dust-producing nature of the operations being performed.

(1) *Minimal setup and isolation.* A minimal setup should be used for operations that generate little or no airborne lead levels in the work area. Because there will be minimal generation of dust and debris, containment may be limited to the immediate work area. Minimal setups consist of protective coverings (typically 0.15-mm [6-mil] polyethylene sheeting) on the floor (or work platform) beneath the work area and extending approximately 3.05 m (10 ft) beyond in all directions. When work is performed on walls, the protective covering must be extended onto the wall and secured to the ceiling (or to at least 3.05 m [10 ft] above the work area). Objects that cannot be removed from the work area must be protected from contamination by the lead dust and debris. All drain openings in the work area must be sealed and plugged to prevent debris from escaping into storm drains and sewers. Access to the work area must be restricted to only those personnel involved in the project, and they must have completed the medical surveillance and lead training programs.

(2) *Moderate setup and isolation.* A moderate setup should be used for operations that generate a moderate amount of airborne lead in the work area. Because of the increased amount of dust generated, a more complicated containment system is necessary. A moderate setup consists of tarpaulins erected on all sides of the work area with joints overlapped to prevent emission of material into the environment. Impermeable tarpaulin materials typically are used. When the removal procedures involve chemical strippers, water- and chemical-resistant materials are used. Polyethylene sheeting is placed under and around the immediate work area. Objects that cannot be removed from the work area must be protected from contamination by the lead dust and debris. When the work area is defined by physical barriers, all openings must be sealed with polyethylene sheeting, and all drain openings in the work area must be sealed and plugged. Access to the work area must be restricted only to personnel involved in the project, and they must have completed the medical surveillance and lead training programs.

(3) *Maximum setup and isolation.* A maximum setup should be selected for operations that generate a large amount of airborne lead and that require the work area to be fully enclosed to establish a complete containment with ventilation. Maximum setups consist of substantial confinement systems, such as those defined as Classes 1, 2, and 3 in SSPC Guide 6I (Con), to contain the work area. Ventilation equipment, with dust collection on the exhaust

air, must be used to reduce worker exposure. Access to the work area must be restricted only to personnel involved with the project, and they must have completed the required medical surveillance and lead training programs.

c. Restricted area. Two methods are used for establishing a restricted area around the removal activities: visual assessment and area sampling. The method to be used depends on the dust-producing nature of the operation being performed within the work area.

(1) *Restricted area by visual assessment.* Visual assessment is recommended when performing short-duration operations, or when the method generates little or no airborne lead. A zone 4.6 to 9.15 m (15 to 30 ft) in all directions of the work area must be isolated using tape, ropes, signs, and similar physical and visible barriers. Signs posted at the entrance and exit to the work area must read as follows: WARNING—LEAD WORK AREA - POISON - NO SMOKING OR EATING.

(2) *Restricted area by area sampling.* Area sampling should be used when the operation generates moderate to maximum amounts of airborne lead, or the project is of long duration. A zone is delineated using tape, ropes, signs, and similar physical and visible barriers. The air is monitored around the zone to establish the boundary beyond which the OSHA action level of $30 \mu\text{g}/\text{m}^3$ will not be exceeded. Area samples are collected during representative operations throughout an entire work shift, and they are measured as an 8-hour time-weighted average (TWA). Specific air sampling procedures are discussed in Chapter 11. Air samples must be submitted to laboratories accredited by the American Industrial Hygiene Association (AIHA) and analyzed according to the National Institute for Occupational Safety and Health (NIOSH) Method 7082, or equivalent, for the appropriate metals analysis. If the results of the analysis determine that the exposure is below the action level, the restricted area should be established at that location. If the results are above the action level, the containment should be improved or the samplers should be moved further away from the work area and the testing repeated. Additionally, warning signs must be posted at the entrance and exit to the work area and should read as follows: WARNING—LEAD WORK AREA - POISON - NO SMOKING OR EATING.

d. Final cleanup. Cleanup applies to all removal activities of lead-containing paint and is imperative for the successful completion of the lead-removal process. Essentially, all visible accumulations of lead-containing materials and debris must be removed from the work area. Methods of contamination removal include HEPA vacuuming and placing debris in sealed containers. All surfaces in the work area, including reusable sheeting and

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tarpaulins, must be cleaned by HEPA vacuuming and wiping with at least 1 percent phosphate detergent or 5 percent trisodium phosphate solutions. All tools, equipment, and reusable tarpaulins must be free of lead contamination prior to removal from the isolated work area. On completion

of cleanup and contamination removal, the work area must be reinspected for visible residue. If any accumulation of residue is observed, the area must be recleaned until no further residue remains.

Chapter 7

Surface Preparation

7-1. Introduction

a. Surface preparation is the key factor in determining the success of a protective coating system. The equipment and techniques that can be used to achieve the desired surface cleanliness and roughness (profile) vary considerably. Traditional methods of surface preparation are now accompanied by new, innovative methods that have evolved mainly because of the issues surrounding the safe removal of lead-containing coatings from industrial structures.

b. The ultimate objective of surface preparation is to create proper adhesion of a coating over an underlying substrate. Adhesion is the key to coating effectiveness. It determines whether the coating is merely a thin film lying on the surface or if it becomes an actual part of the substrate. Adhesion is even more critical for coatings subjected to corrosive or immersion environments. Proper surface preparation is vital to the service life and overall effectiveness of a coating for protection of the substrate. The purpose of surface preparation is twofold.

c. The surface must be roughened, providing an increased surface area for a mechanical bonding of the coating to the substrate. This roughening is commonly referred to as anchor pattern or profile, and it is essentially a pattern of peaks and valleys etched into the surface. This pattern is most commonly obtained by abrasive blast cleaning, although it can be obtained by the use of certain power tools which simultaneously clean and roughen the surface.

d. Cleanliness is essential for adhesion of the coating to the substrate. Coatings applied over rust, dirt, or oil bond poorly to the substrate. Early coating failure usually will result unless the substrate is free from these contaminants.

7-2. Common Methods of Surface Preparation

A wide variety of surface preparation methods exist. Those discussed in this chapter include: solvent cleaning, hand-tool cleaning, power-tool cleaning, water jetting (low and high pressure), chemical stripping, abrasive blast cleaning (wet and dry), vacuum blast cleaning, centrifugal blast cleaning, sodium bicarbonate blast cleaning, sponge jetting, carbon dioxide blast cleaning, and laser removal.

a. *Solvent cleaning (SSPC-SP 1).* Solvent cleaning (SSPC-SP 1) is a procedure for removing detrimental

foreign matter such as oil, grease, soil, drawing and cutting compounds, and other contaminants from steel surfaces by the use of solvents, emulsions, cleaning compounds, steam cleaning, or similar methods that involve solvent or cleaning action. Solvent cleaning is a form of surface preparation used specifically for the removal of oils and greases. It does not remove rust, rust scale, mill scale, or old coating residues from the surface. Poor solvent cleaning technique spreads contamination to an otherwise clean surface because the oil or grease becomes dissolved in the solvent. Immediately on solvent evaporation, the grease remains as a thin film over the entire wiped surface. The bonding of the coating to the steel will be inhibited if a thin film of oil remains on the surface. Oil and grease contamination is extremely common, however, and must be removed before the application of any coating. Solvent degreasing is a practical removal process and is used in conjunction with all the various methods of surface preparation. Three common methods are water washing, steam cleaning, and the use of hydrocarbon solvents.

(1) Water washing. Low pressure water washing is an effective method of solvent cleaning. If alkaline or emulsion cleaners are used, the surface (following washing) must be thoroughly rinsed with clean water to remove any residual film of the alkaline or emulsion cleaners. If not removed, these soap/oil films will adversely affect the adhesion of the subsequently applied coating. If alkaline cleaners are used, the pH of the surface should be checked after the final rinse. The pH should be no greater than that of the rinse water (typically, a pH of 6 to 7 is neutral).

(2) Steam cleaning. Steam cleaning effectively removes grease, oil, and dirt by a combination of detergent action, high pressure heated water (138 °C [280 °F] to 149 °C [300 °F] at 0.189 to 0.315 liters/sec [3 to 5 gal/min]), and impact; and it is used on both coated and uncoated surfaces. The equipment consists mainly of a pressure jet steam cleaner. A separate solution tank or drum frequently is required for preparation of the cleaning solution. One type of steam cleaner stores the concentrated cleaning solution and mixes it with water at a constant rate to generate a uniform cleaning solution. The solution is fed through a heating unit that partially vaporizes the solution and creates pressure. The hot solution and steam are forced through nozzles onto the surfaces to be cleaned. The same equipment can be used for cleaning with super-heated vapor (dry steam) or with cold water under high pressure, and it may be either portable or stationary.

(3) Hydrocarbon solvents. Hydrocarbon solvents are petroleum-based mineral spirits (aliphatics) with a minimum flash point of 38 °C (100 °F), or "Stoddard Solvents" (ASTM D235), and are commonly used as the general

purpose solvent for cleaning under normal conditions. When the temperature is 27 °C (80 °F) to 35 °C (95 °F), high flash aliphatic mineral spirits with a minimum flash point of 54 °C (130 °F) should be used. Heavy mineral spirits with a flash point over 60 °C (140 °F) should be used when the temperature is over 35 °C (95 °F). Aromatic solvents may be used if greater solvency is required; however, they generally are more toxic and have lower flash points. Commonly used aromatic solvents include toluol, xylol, benzol, and high flash naphtha. Benzol (benzene) is highly toxic and explosive, and it should not be used. Because of the relatively low flash points of these solvents, fire and explosion hazards are inherent, and extreme care should be taken to ensure safe working conditions.

b. Hand-tool cleaning (SSPC-SP 2). Hand-tool cleaning is a method of preparing the substrate by the use of nonpower hand tools to remove all loose mill scale, loose rust, loose paint, and other loose detrimental foreign matter. Hand-tool cleaning generally is used only when power-operated equipment is not available, if the job is inaccessible to power tools, or when the job is too small to justify mobilization of power-tool or abrasive-blast-cleaning equipment (e.g., maintenance spot touchup). Hand-tool cleaning is slow and tedious, it is not intended for preparation of large surfaces, and it will not generate the surface roughness required for most industrial protective coatings. Care must be taken so surface contaminants such as oil or grease are not distributed over the entire surface through cleaning operations. Solvent cleaning in accordance with SSPC-SP 1 should be performed prior to hand-tool cleaning. Common hand tools include wire brushes, nonwoven abrasive pads, scrapers, chisels, knives, and chipping hammers.

c. Power-tool cleaning (SSPC-SP 3). Power-tool cleaning, similar to hand-tool cleaning, requires removal of all loosely adherent rust, paint, mill scale, etc. using pneumatic and/or electrically operated tools rather than hand tools. Through careful selection and use, many cleaning operations can be accomplished rapidly and produce satisfactory surface cleanliness by using power-tool cleaning. Impact cleaning tools, rotary cleaning tools, and rotary impact cleaning tools are three common categories of power tools, each with unique characteristics that make them adaptable to different cleaning operations and requirements. Power-tool cleaning equipment may or may not generate sufficient surface roughness (profile), depending on the type of tool selected.

(1) Impact cleaning tools. The design of impact cleaning tools involves a piston-driven chisel which strikes the surface. Chisels can be adapted for both scraping and chipping and are useful when heavy deposits of rust scale,

mill scale, thick old paint, weld flux, slag, and other brittle products must be removed from the surface. Chisels are available in a variety of different shapes and are made of various materials. Impact cleaning tools are available with various handle and throttle styles and should be carefully selected for the specific operations for which they will be used, with consideration for operator safety, convenience, and preference. This minimizes worker fatigue and improves operator productivity. Great care must be exercised when using impact tools. Excessive cutting into the surface will remove sound metal, create sharp burrs, and result in premature coating failure. Also, these tools must be sharp; otherwise, they may drive rust and scale into the surface rather than remove it. Impact cleaning tools typically include chipping and scaling hammers.

(a) A needle scaler (needle gun) is essentially a scaling hammer comprised of a bundle of 2-mm (0.08-in.) steel needles housed and positioned forward of the striking piston. The piston strikes all needles simultaneously, propelling them individually against the surface. Needle scalers adapt to irregular surfaces and are most effective in removing brittle and loosely adherent surface contaminants.

(b) Piston scalers are similar to scaling hammers, except that the piston is also the chisel. This minimizes the axial dimension and permits use in applications with limited access. Piston scalers are available in single- and multiple-piston types; some can be mounted in groups for cleaning larger surface areas.

(2) Rotary cleaning tools. It is difficult, if not impossible, to achieve sufficient surface roughness for most industrial coatings using rotary power tools. Commonly, a polished, glossy surface prevails. Rotary power tools are notorious for spreading oil and grease over the surface; however, solvent cleaning, prior to power-tool cleaning, is required by the SSPC-SP 3 protocol. Rotary cleaning tools are comprised of two basic types of cleaning media: nonwoven fiber wheels with abrasives and cup wire brushes. Both can be used to remove old coating, light mill scale, rust, weld flux, slag, and dirt deposits.

(a) Nonwoven fiber wheels can be composed of various grades of abrasive and densities. Fresh working abrasive provides a constant rate of surface cleaning. Nonwoven fiber wheels containing a resin-mounted abrasive are recommended when base metal should not be removed but when wire brushes are not aggressive enough.

(b) Rotary wire brushes are composed of various shapes and sizes of wire bristles with crimped or knotted bristles. Selection of style and type of bristle abrasive composition is based on manufacturer's recommendations and personal

trial. Wire brushes and nonwoven fiber wheels are manufactured in both cup and radial form.

(3) Rotary impact tools. Rotary impact tools operate on the same basic principle as other impact tools, through cutting or chipping action. However, rotary impact tools use a centrifugal principle in which cutters or hammers are rotated at high speed and thrown against the surface. On pneumatic or electric powered tools, rotary impact tools consist of three major types: heavy duty rotary flaps, cutter bundles (or stars), and rotary hammers.

(a) Heavy duty rotary flaps are uniquely portable tools that use tungsten carbide shot attached to the ends of flexible leather flaps. These flaps are loaded onto a hub, and its rotation impacts the shot against the surface. This fractures old coatings or mill scale and can provide a cleanliness equivalent to "white metal." The process generates a nominal 2.0-mil profile, and it is generally more rapid and thorough than other types of rotary chipping tools. Rotary flaps, while yielding white metal cleanliness and 2-mil profile, do not produce a texture equivalent to abrasive blast cleaning and may not be suitable for some coatings.

(b) Cutter bundles, or stars, consist of hardened steel star-shaped washers that are free to rotate individually on spindles that orbit a powered axis. The scraping is suited for grinding concrete, surface preparation, coating removal, and generation of nonslip surfaces.

(c) Rotary hammers are a series of free-swinging hammers that, through impact on a surface, are used for removal of most industrial coatings and heavy layers of rust and mill scale.

d. Power-tool cleaning to bare metal (SSPC-SP 11). Power-tool cleaning to bare metal requires a greater degree of cleaning than that required by SSPC-SP 3 and has a surface profile minimum of 0.0254 mm (1 mil). Surfaces prepared by this method should be free of all visible oil, grease, dirt, dust, mill scale, rust, paint, oxide, corrosion products, and other foreign matter. The tools used to prepare the surface to SP 11 are similar to those used for SP 3. The availability of SSPC-SP 11 provides an opportunity to select a method of cleaning suitable for certain coatings in areas where abrasive blast cleaning is prohibited or not feasible, yet a greater degree of cleaning is necessary than can be produced by hand and power tool methods. Applications include: touchup of welds or damaged areas created during shipping or erection, reduction of the volume of hazardous waste produced by abrasive blast cleaning, and cleaning around equipment or machinery that is sensitive to airborne aggregate and debris.

e. Low pressure (6,890 to 20,670 kPa [1,000 to 3,000 psi]) water jetting. Low pressure water jetting can be used with or without detergents to remove grease, oil, or other loose foreign debris from the surface. Low pressure water jetting can also be used to meet the requirements of SSPC-SP 1. This method will not remove adherent coatings and, at lower pressures, may not remove loosely adherent paint unless the water stream is directed under the loose edges. This application is best suited for general overall cleaning operations on various items, structures, and substrates. It can be used effectively on wood and concrete/masonry surfaces without creating any damage.

f. High pressure (34,450 to 68,900 kPa [5,000 to 10,000 psi]) water jetting. High pressure water jetting will effectively accomplish all that low pressure water jetting will, as well as the removal of many tightly adherent materials. This method is, perhaps, the most commonly used of water jetting. It provides not only a higher pressure normally required to remove more material from the surface, but also requires water at only approximately 0.63 liters/sec (10 gal/min) to provide maximum cleaning rates and maximum endurance of the operator's physical ability, compared to ultra high pressure water blasting.

g. Ultra high pressure ($\geq 103,350$ kPa [15,000 psi]) water blasting. Ultra high water blasting will effectively remove intact coatings, but it will not remove tight rust or mill scale. This method is capable of cutting through concrete/masonry surfaces and can be more effective compared to abrasive blasting in the removal of coatings similar to coal tar enamels.

h. Chemical stripping. Chemical stripping involves the application of an alkali, acid, or methylene chloride solution to a painted surface by spray, brush, or trowel. The solution remains on the surface for a few hours or overnight to allow the chemical reaction to take place and soften the coating. The stripper and coating are then scraped off, and the surface is scrubbed and washed to remove residual stripper and coating. Following removal, neutralization of the surface is required, depending on the specific product used to provide a surface with a neutral pH. Many of these formulations, because of the chemical used, may cause burn and toxic effects; therefore, protective clothing and respiratory protection should be used as recommended by the product manufacturer. For more detailed information on proper safety practices, see Chapter 10. Recent developments include strippers that are more user friendly and do not contain alkalis, acids, or methylene chloride. Instead, they involve the use of various solvents; but the manufacturer's safety precautions for product use should be followed. These products should not be permitted to

contaminate the soil after use, and they should be properly contained and disposed of. Additionally, concerns are necessary if the coating removal contains lead-based paint (see Chapter 6).

i. *Conventional methods of abrasive blast cleaning—expendable abrasive.* Abrasive blast cleaning is perhaps the most productive method of surface preparation for coatings that require both an anchor pattern and a high degree of surface cleanliness. Blast cleaning is the only method that can completely remove intact rust and mill scale and produce an even roughness with a controlled anchor pattern. Abrasive blast cleaning is the propelling of abrasive materials at speeds of up to 724 kilometers per hour (km/hr) (450 miles per hour [mph]) against a surface. The mass of abrasive, combined with velocity created by the compressed air (620 to 689 kPa [90 to 100 psi]) used to propel the abrasive, creates kinetic energy. This kinetic energy is transferred to the surface and results in efficient removal of rust, mill scale, paint debris, and other surface materials. Simultaneously, a controlled anchor pattern (surface profile) is generated. The SSPC has published reference cleanliness standards for abrasive blast cleaning (SSPC Painting Manual, Volume 2). The National Association of Corrosion Engineers (NACE) has established similar standards that will be discussed later in this chapter (paragraph 7-4a). Each degree of cleaning stipulates a percentage of the surface that must be free of all materials and a percentage of the surface permitted to contain stains, streaks, or discoloration. Conventional blast cleaning generally falls into five categories: open nozzle, water blast with abrasive injection, open nozzle with a water collar, automated blast cleaning, and vacuum blast cleaning. Perhaps the most common method of abrasive blast cleaning is the use of an "open nozzle," by which abrasive media are fed from a hopper through a hose using compressed air.

(1) Equipment. An open nozzle abrasive blast-cleaning operation consists of: the air compressor, air hose (compressor to abrasive pot), moisture and oil separator/air coolers and driers, blast pot, blast hose (abrasive and air), nozzle, and safety-related equipment.

(a) Air compressor. The air compressor is the source of energy for open nozzle blast cleaning. The amount of work accomplished (production) is in direct proportion to the volume of air pressure (cubic feet per minute) at the nozzle. The larger the compressor, the larger the orifice size of the nozzle it can support. The larger the orifice of the nozzle, the more productive the operation can be.

(b) Air hose. The air hose connects the compressor to the blast pot. For efficient blast cleaning, the air hose should have as large an inside diameter as practical to

reduce friction and avoid air pressure loss (a minimum 31.75-mm (1-1/4-in.) inside diameter (i.d.) air hose is recommended; however, air hoses with a 50.8- to 101.6-mm (2- to 4-in.) i.d. are commonly used). If the hose size is too small for the volume of air passing through, frictional losses will cause a loss of pressure and poor blast cleaning efficiency. The air hose should be as short as practical to reduce pressure drop, and contain as few couplings as possible. Because many projects utilize two or more blasters, the air hose must be adequately sized so proper nozzle pressures can be maintained.

(c) Moisture and oil separators/air coolers and driers. Moisture (especially in humid areas) and oil mists (from the lubricating oils in the air compressors) become problems when large amounts of compressed air are used in an abrasive blast-cleaning operation. To combat this, adequately sized oil/moisture separators should be installed at the blast pot (the most distant point from the compressor) to eliminate oil and moisture contamination. Separators are usually of the cyclone type with expansion chambers and small micron filters. Air coolers/driers also commonly are used to treat the air generated by the compressor.

(d) Blast pot. The blast pot (direct pressure machine) is the high production blast machine used in shipyards, refineries, chemical plants, and other facilities for large-scale blast-cleaning operations. The size of the blast pot is generally determined by its abrasive capacity. Therefore, the smaller the pot capacity, the more frequent filling is required. Generally, when blast cleaning extensive square foot areas, a pot that will allow 30 to 40 minutes of blasting without refilling is recommended. Blast machines are available as: portable, mounted on wheels, and in various capacities (number of bags or pounds); or semiportable, with or without wheels, for high production in ton capacities that, in addition, can be equipped with an abrasive hopper for efficient abrasive refilling. The majority of blast pots used on large blasting projects are the gravity-flow type that have equal pressure on top and beneath the abrasive. A typical blast machine consists of air inlet and outlet valves, filling head, metering valve for regulating abrasive flow, and an easily opened hand hole that allows easy access to inspect for wear and removal of any foreign objects that may have fallen into the chamber. If the abrasive used is bulk or recycled, the pot should be equipped with a screen to prevent foreign objects (e.g., cigarette butts, paper, stones, etc.) from entering. When continuous blasting is required, a high-production-type machine, which allows blasting to continue while being refilled, can be used. This type of unit consists of two pressure pots, one mounted over the other. All blasting is done from the lower pot. While blasting from the lower pot, the upper pot is depressurized and refilled. Once the pot is again pressurized, the abrasive is

automatically transferred to the lower pot.

(e) Blast hose. The blast hose connects the blast pot to the nozzle and carries both compressed air and abrasive. A sturdily constructed multi-ply hose with a minimum of 31.75-mm (1-1/4-in.) i.d. is common. A short length of lighter, more flexible hose is sometimes formed at the end. These sections, called whips, are easier to handle than the multi-ply hose and are effective for work in areas with many angles, pipes, and stiffeners. Productivity may be affected because whips have a smaller diameter than the blast hose. Maximum blast efficiency is attained when the length of hose between the blast pot and the nozzle is kept as short and straight as possible. Only externally fitted, quick connect couplings should be used. Internal-type fittings will reduce the inside diameter of the hose, thereby reducing air volume at the nozzle. These fittings also cause air turbulence inside the hose, resulting in an abrasive action where the air and abrasive strike the edge of the internal coupling. The screws that attach the external quick couplings to the blast hoses must not penetrate through the tube because air leaks can occur around these screws. The quick couplings have universal jaws and replaceable gaskets to ensure a good air seal. Quick couplings are available in brass, aluminum, or nylon. Brass has a considerably longer life; however, nylon and aluminum couplings are commonly used because of their light weight.

(f) Blast nozzle. The blast nozzle is a major element in the blast-cleaning operation. Nozzle sizes are identified by the inside diameter of the orifice. Diameters are measured in sixteenths of an inch. For example, a 4.76-mm (3/16-in.) diameter orifice is designated No. 3, a 7.94-mm (5/16-in.) diameter orifice is designated a No. 5, and so forth. Nozzles are commonly available up to 15.9 mm (5/8 in.) in diameter. However, the nozzle can be too large for the air volume being supplied and cause air pressure and production to decrease. Therefore, nozzle size should be as large as permitted by the volume of the air supply to maintain a 620- to 689-kPa (90- to 100-psi) air pressure at the nozzle. Nozzles are available in an assortment of lengths, orifice sizes, lining materials, and configurations. Nozzles may be lined with tungsten carbide, boron carbide, ceramic, or cast iron. Ceramic and cast iron are considered short-life nozzles; tungsten and boron carbide nozzles are long life. The average life of tungsten carbide nozzles is 200 hours; ceramic and cast iron nozzle life averages 2 to 4 hours. Boron carbide nozzles can have a 1,500-hour life if properly handled to prevent cracking of the brittle carbide material. For difficult to reach areas, nozzles are available in right angle configurations, enabling the blaster to propel abrasive around corners. Venturi designed nozzles have a tapered interior shape that increases the abrasive exit speed up to 724 km/hr (450 mph) to create a larger, more even

blast pattern. Production cleaning rates can be increased by as much as 30 to 50 percent with the use of a venturi nozzle over a conventional "straight bore" nozzle. Longer nozzles, from 127 to 203 mm (5 to 8 in.), will more easily remove tightly adherent deposits and increase cleaning rates. However, short nozzles (76 mm [3 in.] or less) may have to be used behind beams or in otherwise relatively inaccessible areas. As the abrasive material flows through the nozzle, the lining wears away and the cleaning effectiveness is reduced. Nozzles should be replaced when wear increases the opening of the original orifice size to the next larger size. Use of worn nozzles will result in increased compressor wear, increased abrasive consumption, and reduced productivity. Nozzle diameter, air pressure, and air volume are all critical. At 620 kPa (90 psi), a 9.5-mm (3/8-in.) nozzle will consume 81.66 liters/sec (173 cubic feet per minute [cfm]) of air, and a 12.7-mm (1/2-in.) nozzle will consume 145.85 liters/sec (309 cfm) of air. Because production is in direct proportion to the volume and pressure of air at the nozzle, a 12.7-mm (1/2-in.) nozzle is capable of generating almost 179 percent of the cleaning accomplished with a 9.5-mm (3/8-in.) nozzle if there is sufficient air available to maintain the nozzle air volume pressure at 620 kPa (90 psi). If the nozzle air pressure with a 12.7-mm (1/2-in.) nozzle drops to 482 kPa (70 psi) because of an inadequate air supply, air consumption drops from 145.85 to 118.95 liters/sec (309 to 252 cfm). Therefore, a 137.8-kPa (20-psi) drop in nozzle pressure causes a loss of 26.9 liters/sec (57 cfm), or 18.4 percent in the cleaning rate (57 divided by 309, multiplied by 100 percent).

(g) Safety. Manually operated air inlet and outlet valves were used in the past to shut down the blast-cleaning operations. Today this has been replaced by the remote-controlled deadman. These remote-controlled devices have been designed to fit any existing blast pot setup, and they are operated at the blast nozzle. They eliminate the need for a pot tender and provide a high degree of safety to the worker because, with the remote control deadman valves, the moment the grip on the nozzle is relaxed, the abrasive pot shuts down. Blasters frequently consider the deadman a nuisance because they must constantly hold down the lever while blasting, and they tend to override the safety feature of the deadman by inserting wedges or tying down the lever. This can be extremely dangerous, especially if the blaster trips and drops the blast hose because the abrasive flow will continue until the wedge or wire is removed or the pot tender shuts the operation down. Other safety and health practices related to abrasive blast-cleaning operations include: respiratory protection, skin protection, eye protection, ear protection, and fire/explosion prevention. A more in-depth discussion of safety during blast-cleaning operations is provided in Chapter 10.

(2) Blast cleaning techniques.

(a) Blast-cleaning techniques are essential for an effective, efficient blast-cleaning operation. The blaster must maintain the proper abrasive flow, angle of attack, and distance between the nozzle and the surface. Experimentation with different angles and distances when starting a new job will determine what is most effective for the surface condition.

(b) The proper balance of abrasive and air is achieved when the abrasive airstream from the nozzle is "bluish" in color. Experience is ultimately the best indicator. Many operators tend to use too much abrasive, reducing speed and increasing airborne dust and cleanup cost. The air/abrasive mixture is adjusted using the metering valve, or carburetor, at the base of the abrasive pot.

(c) The angle of the nozzle to the surface can range from 45 to 90 degrees. To remove rust and mill scale, an 80- to 90-degree angle to the surface is preferred. This angle also is suitable for dislodging contaminants from pitted surfaces. A slight downward angle also directs the dust away from the operator. To peel old paint and layers of rust from the surface, a 45- to 70-degree angle to the surface is most productive.

(d) The closer the nozzle is to the surface, the smaller the blast pattern. With a small pattern, the abrasive is concentrated in a smaller surface area, resulting in an impact at greater speed and more force. In a small surface area, the operator can blast more area for the energy spent but will cover less area in a given time. A distance of only 152.4 mm (6 in.) may be required to remove tight mill scale and heavy rust, but a 457.2-mm (18-in.) nozzle-to-surface distance may be most effective for removal of old coating. Each pass should be straight and at the same distance to produce a uniform pattern.

(3) Quality control.

(a) Air pressure. Reading the pressure gage on the compressor or on the blast pot reveals the air pressure at those points only. Friction losses and pressure drops through the pot, hoses, etc. all reduce nozzle pressure. Nozzle pressures of 620 to 689 kPa (90 to 100 psi) are considered optimum. Lower pressures reduce blast-cleaning efficiency. Although higher pressures do not greatly increase efficiency, they do lead to operator fatigue. The air pressure at the nozzle is measured using a hypodermic needle pressure gage. The gage needle is inserted into the blast hose as near to the nozzle as possible. The needle must point in the direction of the abrasive flow, and the measurement is made while the abrasive and air are flowing. The gage reading indicates air pressure at the nozzle.

(b) Air cleanliness. Compressed air cleanliness can be determined in accordance with ASTM D4285 by exhausting the compressed air (downstream of moisture and oil separators) onto a clean white cloth or blotter paper. Air cleanliness should be evaluated each day prior to commencing blast cleaning work, and as required thereafter to help ensure a clean, dry air source.

(c) Nozzle orifice. The orifice size of a blast-cleaning nozzle can be monitored for wear using a nozzle orifice gage. Similar in appearance to a ring sizer, the gage measures the inside diameter of a nozzle internally. A china marker (grease crayon) is used to mark the side of the cone. The gage is then inserted into the blast nozzle, twisted slightly, then removed. The nozzle opening will etch the grease crayon marking, which coincides with scale divisions (inches and cfm at 100 psi) to reveal the interior diameter.

(d) Abrasive cleanliness. Abrasive materials contaminated with oil or chemical residue can lead to surface contamination. Abrasives should be monitored for cleanliness using either of the following techniques. The first method, the "vial test," is referenced in SSPC Painting Manual Volume 2 Abrasive Specification No. 1, "Mineral and Slag Abrasives" (SSPC-AB 1). With this test, if the abrasive is contaminated, the top of the water in the vial will reveal a film of grease or oil. The abrasive also can be tested for chemical contamination by performing a conductivity test, per ASTM D4940. However, water-soluble contaminants such as salt will not be detected using these tests. If water-soluble contaminants are present, a litmus paper test of the water in the vial will tell if they are acid or alkaline. If neutral, a drop of 5 percent silver nitrate solution should be added to the water. The formation of a white precipitate will indicate the presence of chlorides. Alternatively, after the water has evaporated, if these contaminants are present, salt crystals would be detectable.

(e) Ambient conditions. Ambient conditions typically do not affect rough blast cleaning; however, for final blast-cleaning operations, ambient conditions must be monitored, and work should be halted if temperature, relative humidity, dew point, and surface temperature conditions are outside of the contract requirements. Most importantly, the surface temperature should be at least 3 °C (5 °F) higher than the dew point for final blast-cleaning operations. This precautionary step will preclude moisture formation on the surface. A more in-depth discussion on measurement of ambient conditions is in Chapter 9.

j. Abrasive blast cleaning with recyclable abrasives. Abrasive blast cleaning with recyclable abrasives can be performed using compressed air to propel the abrasive similar to blast cleaning with expendable (nonrecyclable)

abrasives, or without compressed air using centrifugal force to propel the abrasive.

(1) Centrifugal blast cleaning. Centrifugal blast cleaning is widely used in steel fabrication shops for several reasons: it is relatively fast, consumes less energy and blasting abrasive, and allows for recycling abrasive. The principles of operation for centrifugal wheel blasting equipment are fairly simple. The steel to be cleaned is conveyed through a cabinet or enclosure where blast-cleaning abrasive is hurled at the steel surface from various directions by rotating wheels with blades. The bladed wheels rotate rapidly enough to propel the abrasive at speeds of up to 322 km/hr (200 mph). The spent abrasive, rust, mill scale, etc. fall to the bottom of the cabinet where a separator removes the fines, rust, and mill scale from the abrasive so the abrasive can be reused. The bladed wheels are motor driven and are typically capable of hurling approximately 362.4 kilograms (kg) (800 pounds [lb]) of abrasive per minute; an airblaster with a 9.5-mm (3/8-in.) diameter nozzle delivers only approximately 31.7 kg (70 lb) of abrasive per minute. The degree of blast cleanliness obtained can be altered by a number of methods. Generally speaking, the requirements of SSPC-SP 10 can be met by conveying the steel to be cleaned at the rate of 1.2 to 1.8 meters/min (4 to 6 linear feet per minute). Greater or lesser degrees of surface preparation can be achieved by regulating the speed of the conveyor or the velocity at which the abrasive is hurled toward the steel. In some cases, it may be necessary to convey a piece of steel through more than once to attain a high degree of surface cleanliness or to assure that all of the surfaces have been exposed to the cleaning action of the abrasive.

(2) Airblast cleaning. Airblast cleaning with recyclable abrasives can involve a permanent shop-type setup, including a blast room. The floor generally consists of steel grating to allow the passage of spent abrasive to be recycled into the system for reuse. Similar to centrifugal blast cleaning, during the abrasive recycling, dust fines, mill scale, rust, and other contaminants are filtered out. Airblast cleaning with recyclable abrasive also can involve the same equipment previously discussed using expendable abrasives. The only difference is the abrasive is recycled manually and sifted through screens to eliminate foreign debris.

(3) Vacuum blast cleaning. Vacuum blast cleaning uses compressed air to propel abrasive particles against the surface to be cleaned. The blast nozzle is fitted into a localized containment assembly (surrounding the nozzle only), which is equipped with a vacuum. As a result, dust, abrasive, and coating debris are vacuumed simultaneously with the blast-cleaning operation. Debris is separated for disposal, and the abrasive is returned for reuse. Metallic

abrasives are commonly used. When properly used, vacuum blast cleaning can significantly minimize, or eliminate, airborne dust and debris, which is of major importance when removing lead paint. The volume of debris also is significantly reduced compared to open abrasive blast cleaning with disposable abrasives because it is composed of only abrasive fines and pulverized paint. Vacuum blast cleaning is capable of producing the highest degree of surface preparation on large, open surfaces, but it does not have the same capability in areas of difficult accessibility. In fact, the greatest limitation of vacuum blast cleaning is that, to eliminate dust and to recycle all of the abrasive, the mask or brush surrounding the blast nozzle must be held tightly to the surface at all times. This is not possible on irregular surfaces. Even on flat surfaces, productivity is limited by a small blast pattern and the need to maintain a seal between the head and the surface, which also adds to operator fatigue.

(4) Recyclable abrasives. Recyclable abrasives generally are not used in the field unless a reclaiming and recycling system is used primarily because of the higher costs of recyclable abrasives (e.g., steel shot and steel grit). By using a recycling system, the abrasive can be reused numerous times before replacement with new abrasive becomes necessary. For projects in which the generation of dust emissions and spent abrasive must be contained and controlled, steel grit is the preferred choice of a recyclable abrasive.

(5) Monitoring abrasive size and methods. Control of the work mix (size) is vital in maintaining a consistent production rate and surface profile. Representative samples of the work mix, which actually performs the cleaning and provides the finish (anchor pattern), should be subjected frequently to careful sieve analysis to be certain that the size distribution of the work mix is in balance, i.e., not predominantly coarse or fine. The larger pellets in the work mix impart the greatest impact energy per pellet, cause cracking or fragmenting of heavy surface contaminant on the area being cleaned, and impart indentations of maximum peak-to-valley values. Medium and smaller pellets in the work mix provide greater coverage for scouring and complete removal of cracked or fragmented surface contaminant. Because of the decreased impact energy of the smaller abrasive particles, the peak-to-valley value is decreased. Also, because of the small size, a greater number of impacts occur on a given area of the work piece and greater peak population results. Each abrasive type, size, and shape has its own inherent impact life cycle, generally measured in pounds used per blasting hour. Theoretically, new abrasive should be added to the system every blasting hour in amounts equal to the rate of withdrawal, or loss, from the system. In practice, however,

making additions once a shift, or every 8 hours, is acceptable. A continuous, automatic system of abrasive replenishment is the preferred and most reliable method of maintaining a uniform work mix in a production operation. Delay in making new abrasive additions tends to decrease the percentage of coarser sizes in the work mix; the result will likely be poorer quality cleaning and reduction of anchor pattern depth. Conversely, adding a large quantity of new abrasive at one time increases the percentage of coarser sizes; this results in a coarsening of surface profile and, for a given period, insufficient coverage and poorer cleaning. Maintaining a uniform and stabilized operating mix also requires the abrasive particles removed from the blast machine to be of uniform size. To realize the greatest economic benefits of using metallic abrasives, the particle size removed should be smaller than the smallest size that is effective in the cleaning operation. Control of removal size requires careful attention to the adjustment of the separator system and of the airflow through the separator.

(6) Abrasive cleanliness and methods. Although there is no inspection apparatus for determining the cleanliness of the abrasive to be used, a visual inspection must be made to assure that it is not damp or contaminated. When abrasive recycling systems are used, tests for contamination should be conducted as discussed under paragraph 7-2i(3)(d).

k. Wet/water abrasive blast cleaning.

(1) Wet abrasive blast cleaning involves the incorporation of a small amount of water into a dry abrasive blast-cleaning operation. Methods, equipment, and techniques are similar to dry abrasive blast cleaning, except that a modified nozzle is used in which water is either injected into the blast stream or introduced to the abrasive as a "collar" around the exit stream.

(2) Water abrasive blast cleaning uses high pressure water and abrasive to provide a cleaned and roughened surface. Basically, a small amount of abrasive is fed into the water stream. The equipment, methods, and technique are similar to wet blast cleaning, except an abrasive supply is provided for injection into the water stream. The advantages of wet abrasive blast cleaning include the control of dust emissions and aid in the removal of chemical contamination by the introduction of water. The advantages of water abrasive blast cleaning include providing a surface profile when compared to the water blast-cleaning method without abrasive. The limitations of wet abrasive blast cleaning include the accumulation of considerable amounts of abrasive on the surface because of a lesser amount of water in and around the abrasive stream, which requires an extra step of cleaning (washing) to remove the spent abrasive. A limitation of both wet and water abrasive blast

cleaning is that the prepared steel surfaces will oxidize quickly because of the presence of water. Therefore, rust inhibitors must be used to prevent the oxidation process.

(3) Flash rusting can occur within minutes after blasting with water. To prevent oxidation or flash rusting, a suitable inhibitor usually is injected into the blast hose or applied after blast cleaning. A rust inhibitor with a solution strong enough to retard rust after the final rinsing of the contaminants and spent abrasives has been completed should be used. Inhibitors include soluble chromates, phosphates, nitrates, and molybdates. When dry, certain inhibitors leave salts that could produce adhesion problems for protective coatings. Therefore, the inhibitor must be compatible with the paint system to be applied. Inhibitors also must meet USEPA requirements and be nonpollutants. It may be preferable to apply the inhibitor solution after the water blast operation to minimize operator exposure, save inhibitor, reduce problems of liquid pollution, and reduce the risk of excessive flash rust. The air-drying feature of the air-water-sand method is highly beneficial in minimizing flash rusting.

l. Sodium bicarbonate blast cleaning.

(1) Sodium bicarbonate blast cleaning is an innovative method for coating removal. Compressed air or high pressure water is used to propel abrasive particles of sodium bicarbonate (baking soda) against the surface to be cleaned. Sodium bicarbonate is water-soluble; therefore, the coating chips can be separated from the water (and dissolved sodium bicarbonate) to reduce the total volume of waste material.

(2) The equipment is specialized and consists of an air compressor, water, sodium bicarbonate abrasive, a means of collecting the coating debris and water, and a system for separating the coating chips from the water and dissolved bicarbonate. A blast pot, blast hose, and specialized nozzle are required for airblast systems. The nozzle is equipped with a means of introducing water to the abrasive immediately prior to exiting the nozzle. For water systems, a specialized pump is used (typically less than 41,340 kPa [6,000 psi]) to convey high pressure water to the nozzle. A special nozzle assembly is used to inject the sodium bicarbonate (from a blast pot) into the water stream at the nozzle.

(3) Sodium bicarbonate blast cleaning has inherent advantages and limitations. This method will remove coatings, dirt, grease, machine oil, and various process residues; but it leaves mill scale and rust unaffected. If mill scale and rust are present, some degree of mechanical removal may be required prior to coating. The addition

of a small percentage of expendable abrasive can assist in the cleaning and enhance the removal of mill scale and rust. If the original surface was blast cleaned, the profile is often "restored" after the coating is removed, and the surface becomes suitable for painting.

(4) The residual sodium bicarbonate left on the surface provides a slight passivation to the surface (pH 10), which prevents most of the flash rusting potential common when using wet abrasive blasting methods. Sodium bicarbonate blast cleaning is relatively slow compared to the productivity of open nozzle abrasive blast cleaning. Sodium bicarbonate blast cleaning can be effectively used by many industries such as pulp and paper, food processing, petrochemical, and others when plant shutdowns are undesirable.

m. Sponge jetting.

(1) Sponge jetting or sponge blasting is an innovative method of preparing a surface for painting. Compressed air is used to propel particles of manufactured polyurethane sponge against the surface to be cleaned. The sponge particles can be impregnated with abrasive for the removal of coatings, rust, and mill scale. After use, the sponge and debris are collected, loaded into a vibrating screen and/or wet separation system, and the reusable portion of the sponge is returned for additional blast cleaning. The inception of sponge jetting began with a simple urethane foam sponge designed solely as a degreasing media. Similar urethane sponge particles were then impregnated with a nonsilica-containing mineral abrasive and garnet (both identified, respectively, as mildly aggressive and aggressive blast media when combined with sponge material). These materials permitted simultaneous degreasing and rust/coating removal operations and surface profile generation. Aluminum oxide and steel grit have also been incorporated with the sponge jet material.

(2) The specialized equipment required for sponge jetting includes an air compressor, blast hoses and special blast nozzle, specialized blast pot, abrasive collection equipment (e.g., vacuums), and vibrating screen abrasive reclaiming equipment. Screens or tarps to isolate the work area along the ground are typically sufficient to capture the abrasive and debris for return to the separation system. Fine dust particulate, typically associated with open abrasive blast cleaning using expendable abrasives, is not visually apparent with this method.

(3) Sponge jetting, as with all removal methods, has inherent advantages and limitations. The visible dust created when using sponge jetting is substantially reduced compared to open blasting with expendable or recyclable

abrasives. The volume of debris also is reduced substantially because the sponge abrasive is typically reused from 5 to 15 times. The method offers the same advantages as abrasive blast cleaning with regard to the superior degree of cleaning and the ability to clean areas of difficult accessibility, but the productivity is 25 to 50 percent that of open nozzle blast cleaning, depending on the condition of the surface to be cleaned. When compared with other dry methods of abrasive blast cleaning, some form of containment is still required to capture rebounding sponge abrasive and debris. The costs of the equipment and sponge media are high. Although sponge jetting is a relatively new method of preparation, it is similar enough to open nozzle abrasive blast cleaning that operators can easily adjust to the process. In addition, this process minimizes waste generated as in conventional surface preparation methods and provides increased worker and public safety by minimizing adverse effects to the environment during surface preparation activities.

n. Carbon dioxide (dry ice) blast cleaning.

(1) Dry ice pellets can be used as an abrasive media to remove coating materials from a surface. Basically, compressed air is used to propel rice-sized pellets of carbon dioxide (dry ice) against the surface to be cleaned. The abrasive dissipates, leaving only coating debris for disposal. Liquid carbon dioxide is converted to pellets with specialized equipment and conveyed through a blast hose and special nozzle assembly. This method is capable of removing coatings, but it leaves mill scale and rust unaffected. If the original surface was blast cleaned, the profile is "restored" after the old coating is removed. Carbon dioxide blast cleaning is a remarkable concept, and it may represent trends in removal methods of the future. Carbon dioxide will not create a spark or conduct electricity; therefore, it can be considered for use in areas where the possibility of sparking is unacceptable. The abrasive dissipates and reduces the volume of waste to only the coating being removed. In addition to the reduction in the volume of waste generated, containment requirements also are reduced because of the low dusting created during removal.

(2) Carbon dioxide blast cleaning is not without limitations. The equipment is expensive, and a large supply of liquid carbon dioxide (e.g., tank truck) is required in addition to other specialized equipment for producing the carbon dioxide pellets and dispensing them through a blast nozzle. The pellets will not productively remove mill scale or heavy rust, and coating removal also is slow. One advantage of using this method, particularly in a confined space, is that it does not produce the dust generated with abrasive blast cleaning.

o. Laser removal. Research studies have shown that mill scale and other adhering deposits can be removed, at least to some degree, when subjected to thermal shock of chemical decomposition using laser beams. The testing of this process revealed that, when rusted steel was exposed to laser beams of several kilowatts, the hydrated oxides were changed to a dense, hard scale of magnetite that then could be removed. Laser cleaning probably will not have much impact on the cleaning of structural steel in the near future because of significant energy input and equipment development requirements.

7-3. Abrasive Type and Selection

a. Abrasive selection. The surface effects produced with various abrasives can range from deep cutting to gentle scouring of the surface. Important factors to consider in selecting an abrasive include: type of surface to be cleaned, shape of the structure, type of material to be removed, surface finish desired, profile, breakdown rate of the abrasive, reclamation of the abrasive, hazards associated with the use of the abrasive, and the area in which the abrasive will be used and its danger to surrounding equipment.

b. Abrasive types. The types of available abrasives vary from one part of the country or the world to another. The general categories are: steel shot, metal grit, and mineral abrasives. Each type of abrasive cleans in a different way and leaves a slightly different surface texture. There is a recommended physical and chemical property reference for mineral and slag abrasives as defined by SSPC-AB 1. In addition, several ASTM test methods exist that deal with all abrasives and include the following: C128, C566, C702, D1125, D4417, D4940, and E1132.

(1) Natural oxides. Natural oxides such as silica sand were perhaps the most widely used natural oxides because of their availability, low cost, and effectiveness. The hazards of silica have been elucidated by both USEPA and OSHA, and the use of silica abrasive has been restricted in many areas. Another natural abrasive, also a silica material, consists of a blend of coarse and fine staurolite sands mined from mineral deposits in Florida. It is characterized as an efficient cutting abrasive and has less dusting and a lower breakdown rate than silica sand.

(2) Metallic abrasives. Metallic abrasives such as steel shot and grit abrasives are efficient, hard, and create less dust; but care must be taken to properly store the abrasive to prevent rusting. The initial cost is higher than most other abrasive types, but these abrasives may be recycled many times to make them more cost effective. A combination operating mix of both steel shot and steel grit abrasives is

common.

(3) Slag abrasives. Slag abrasives (ore smelting by-products) are fast cutting, but they have a high breakdown rate and generally are not recycled. These abrasives are the most likely to exhibit a pH on the acidic side.

(4) Synthetic abrasives. Synthetic abrasives (aluminum oxide and silicon carbide) exhibit cleaning properties similar to the metallics, without the problem of rusting. They are extremely hard, fast cutting, and low dusting; but they are costly and must be recycled for economic use.

c. Characteristics. Proper abrasive size and hardness are essential to produce the necessary cleanliness and profile. The characteristics of an abrasive related to performance include size, hardness, and abrasive shape.

(1) Size. A large-sized abrasive particle will cut deeper than a smaller size of the same composition and shape to provide a deeper surface profile. However, the greatest cleaning rate is achieved with the smaller abrasive because of a larger number of impacts per unit area. Abrasive particles larger than 16 or 18 mesh may gouge the metal surface, resulting in a slower cleaning rate. Fine particles (80 mesh size or finer) cannot achieve the 0.038 to 0.063 mm (1.5 to 2.5 mil) profile usually desired for industrial coatings. Particles in the 40- to 50-mesh range commonly are used.

(2) Hardness. Hard abrasives generally cut deeper and faster than soft or brittle abrasives. A hard, brittle abrasive will shatter on impact, reducing its cleaning power.

(3) Abrasive shape. The shape and size of abrasive grains determine the type of surface profile achieved. Because steel shot is round, it peens the surface. Therefore, shot is particularly effective in removing brittle deposits such as mill scale. Grit is angular in shape and produces a jagged finish by cutting rather than peening, which generally is preferred for coating adhesion. A wide variety of surface patterns are available from different grits.

d. Recyclable versus nonrecyclable. Abrasives are categorized into various classifications; some can be recycled effectively but others cannot because of their breakdown characteristics. Nonrecyclable abrasives are not as expensive as recyclable abrasives and should be used for economic reasons if recycling is not to be performed. Generally, abrasives should not be recycled if the breakdown rate is greater than 10 percent; as increased airborne dust, insufficient surface profile, and decreased blast cleaning productivity will likely result. Recyclable abrasives are harder and do not break down as quickly as

nonrecyclable abrasives, and they can be reused.

e. Cleaning/consumption rates. As with all cleaning operations, differences in surface condition, type of steel, corrosion, etc. affect the production rates of cleaning. Conditions are listed in Table 7-1 for open air blast cleaning rates and abrasive consumption on newly fabricated steel using a 9.5-mm (3/8-in.) blast nozzle and 689-kPa (100-psi) nozzle air pressure prepared to an SSPC-SP 10 requirement.

f. Embedment. Some abrasives, particularly softer abrasives, tend to break down and embed particles into the surface profile, which makes it extremely difficult to obtain a specified blast cleanliness (e.g., SSPC-SP 5). In addition, their embedded particles frequently are extremely difficult to remove by brushing and vacuuming.

g. Chemical cleanliness. The pH of an abrasive should be nearly neutral when the abrasive is mixed with water. Most suppliers note the pH on the technical data sheet accompanying the abrasive. The pH value is easily checked and should be routinely monitored. An abrasive with an acid pH would cause premature corrosion of steel and could cause coating failure. pH can be verified using litmus

paper. Soluble chloride is important because chlorides in an abrasive will leave a chloride residue on the blasted substrate that could be detrimental to the substrate and subsequent coating systems. Most chemical laboratories can routinely analyze for soluble chlorides. If the abrasive source is near seawater, routine checking for soluble chlorides is a must.

h. Dust generation. Dust generation is described as the amount of dust generated by an abrasive on impact. Excessive dust can create visibility problems during blasting and cause environmental problems at the jobsite. Generally speaking, the silica sands, boiler, and nickel slag abrasives have the highest degree of dust generation. On the other hand, manufactured abrasive such as silicon carbide steel shot and aluminum oxide have the lowest dust generation.

i. Profile yield. Selection of the proper abrasive depends on the desired surface profile heights, which in turn assures good coating adhesion and performance. Thicker coating films require deeper surface profiles. Steel shot has been found to be adequate for profiles less than 0.076 mm (3 mil). Boiler slag or coarse steel grit may be required to attain profiles of greater depth. The mass and hardness of

Table 7-1
Examples of Cleaning Rates with Typical Abrasives

Abrasive	Abrasive Consumption	Production Rate	Comments
Silica sand 16/40 mesh	12.69 kg/sq m (2.6 lb/sq ft)	0.44 sq m/min (4.75 sq ft/min)	0.038 mm (1-1/2 mil) etch dusty
*Garnet 36 grit	*17.58 kg/sq m (3.6 lb/sq ft)	0.33 sq m/min (3.55 sq ft/min)	0.038 mm (1-1/2 mil) etch - very little dust-reusable
*Aluminum oxide 36 grit	*15.13 kg/sq m (3.1 lb/sq ft)	0.42 sq m/min (4.58 sq ft/min)	0.038 mm (1-1/2 mil) etch - very little dust-reusable
*G-40 steel grit	*26.85 kg/sq m (5.5 lb/sq ft)	0.28 sq m/min (3.06 sq ft/min)	0.063 mm (2-1/2 mil) etch - no dust gray metal-reusable
Crushed flint 12/30 mesh	17.58 kg/sq m (3.6 lb/sq ft)	0.25 sq m/min (2.69 sq ft/min)	0.076 mm (3 mils)-reusable
Staurolite 50/100	15.13 kg/sq m (3.1 lb/sq ft)	0.45 sq m/min (4.85 sq ft/min)	0.013 mm (1/2 mil) etch smooth surface
Coal slag 16/40 mesh	15.62 kg/sq m (3.2 lb/sq ft)	0.36 sq m/min (3.83 sq ft/min)	0.063 mm (2-1/2 mil) etch reusable-imbedding
Copper slag 16/40 mesh	15.13 kg/sq m (3.1 lb/sq ft)	0.40 sq m/min (4.36 sq ft/min)	0.05 mm (2 mil) etch reusable-imbedding

* These abrasives are normally reused.

an abrasive will dictate the depth of the profile on the steel it strikes. The size of the abrasive selected also will affect the number of peaks per square inch. Although abrasives can be recycled, they break down over time. Each abrasive type has its particular rate of breakdown expressed in pounds consumed per hour. To maintain the same degree of blast cleaning, new abrasive media should be added to the working mix at roughly the same rate as the abrasive disintegrates. And new blast material should be added on a daily basis to maintain the working mix.

j. SSPC-AB 1. The SSPC-AB 1 is a specification for evaluation of mineral and slag abrasive blast-cleaning media. It contains specifications and criteria for abrasive properties including: specific gravity, hardness, weight change on ignition, water-soluble contaminants, moisture content, oil content, and crystalline silica content.

7-4. Surface Preparation Standards and Specifications

a. Steel surfaces. The SSPC and NACE have developed surface preparation standards and specifications for steel surfaces. Blast-cleaning standards and specifications will be discussed in this paragraph. SSPC Painting Manual Volume 2 provides more detailed information for these standards. The written standards are supplemented by SSPC VIS 1-89, which photographically depicts the appearance of four grades of blast cleaning over four initial mill scale and rust grades. The standards are visually compared with the prepared surface to determine the degree of cleanliness achieved. The final two pages of VIS-1 illustrate a white metal blast cleanliness using three metallic and three nonmetallic abrasives. The resulting surfaces have slight color and hue differences caused by the type of abrasive media used. In contrast, NACE encapsulates metal test coupons in a plastic media rather than relying on photographic representation. Each encapsulated plate contains representative surfaces blast cleaned to the four grades of cleanliness. NACE standards are prepared for sand, steel grit, slag, and steel shot abrasives. The blast cleanliness specifications are:

(1) SSPC-SP 7 or NACE #4. Removal of all loose materials; tight materials may remain if they cannot be loosened by a dull putty knife.

(2) SSPC-SP 6 or NACE #3. Two-thirds of every square inch (surface area) is cleaned to white metal; one-third of every square inch (surface area) may have stains, streaks, discolorations only; pitted steel may have traces of rust/paint in pits.

(3) SSPC-SP 10 or NACE #2. Ninety-five percent of

every square inch (surface area) is cleaned to white metal; 5 percent of every square inch (surface area) may have stains, streaks, or discoloration only.

(4) SSPC-SP 5 or NACE #1. One hundred percent of every square inch (surface area) must be clean and have a gray-white appearance.

b. Concrete surfaces.

(1) Sweep blasting. Concrete can be prepared by "sweep blasting." The nozzle is held further from the surface than when blasting steel, and the blasting rate is much faster. Sweep blasting will remove any weak surface layers of concrete (laitance), open bug holes, and provide a sound, slightly roughened surface for coating adhesion. Abrasive blast cleaning of concrete can be performed, but lower nozzle pressures (275.6 to 344.5 kPa [40 to 50 psi]) should be used to avoid damaging the concrete by exposing heavy aggregate or reinforcement steel. ASTM D4259 covers three specific methods of surface preparation: mechanical cleaning using rotary impact, vertical impact, and circular grinding tools; water blast cleaning using high pressure water blasting equipment; abrasive blast cleaning using either dry abrasive blast equipment or dry abrasive blast equipment with water injection.

(2) Acid etching. ASTM D4260 provides the procedures for acid etching. Two purposes of acid etching are to neutralize the surface to be coated and to etch the surface to remove the glaze. The surface must be rinsed immediately after acid etching is performed to avoid formation of salts on the surface, which are difficult to remove. The surface should be re-etched if the texture is not of medium sandpaper texture after the first etching treatment. Acid etching will not remove grease or oil; therefore, if these substances are suspected to be present, the concrete should be scrubbed with detergent, soap, or a trisodium phosphate solution prior to acid etching. Steam cleaning also may be required. When concrete surfaces are steel troweled, they may become dense, smooth, and glazed and the paint will not adhere to the surface. In this situation, it may be desirable to etch the surface. A simple method to determine whether etching is required is to pour a few drops of water on the surface. Etching is not necessary if the water is quickly absorbed. Glaze may be removed by rubbing with an abrasive stone, lightly sandblasting, or allowing the surface to weather for 6 to 12 months. The glaze also may be removed by treatment with a solution of 3 percent zinc chloride plus 2 percent phosphoric acid to etch the surface. This solution is not flushed off but is allowed to dry to produce a paintable surface. Acid cleaning methods may be necessary in certain instances to neutralize concrete and masonry surfaces before applying a coating that is

sensitive to alkali. Detection of free alkali should be performed using pH paper, especially if acid washing or etching has been performed, in accordance with ASTM D4262.

(3) Problems with form release agents. Waxes or various resins are often used to prevent possible problems during stripping operations. These compounds vary considerably in their composition and their ability to support adhesion at a later date when an organic coating is applied. Subsequent adhesion testing always is required to determine whether or not form releases were used.

(4) Concrete curing agents. Concrete curing agents frequently are sprayed onto architectural and engineered concrete walls unless their use is specifically prohibited in the specification. However, if these agents are not used and if some form of moist-curing is not used on the concrete, crazing and/or shrinkage cracking probably will occur because of the rapid volume changes that act to create internal stresses within the hydrating matrix of the concrete. Blasting with an approved abrasive solves the problem of removing light contaminants and curing compounds from most concrete surfaces. Sometimes a second pass is required to remove the weak layer of laitance and to open any voids or larger honeycombs.

(5) Moisture content. Underground below grade concrete surfaces and concrete slabs or exterior walls subject to moisture may be subjected to excessive capillary moisture or hydrostatic pressure. This condition may be determined easily by a portable moisture meter instrument as well as by following the test method in ASTM D4263. This method involves taping a segment of plastic sheet to the concrete and allowing the sheet to remain in place for at least 16 hours; the sheet then is removed and the concrete surface as well as the sheet are visually examined for the presence of moisture.

c. Galvanized surfaces. Galvanized steel has a very smooth, comparatively hard surface; consequently, the lack of profile results in potential adhesion problems. The zinc may have a mill-applied surface treatment to prevent wet storage stain; this usually is a chromate passivation treatment. Unsuitable pretreatments can lead to delamination of applied paints. The methods of galvanized surface treatments follow.

(1) Solvent cleaning. When coating galvanized surfaces, certain procedures need to be considered to assure adequate coating adhesion. Oil or grease should be removed by wiping or scrubbing the surface with proper types of rags or brushes wetted with a suitable solvent. The final wiping should be done with clean solvent and clean rags or brushes

so oil and other contaminants will be dispersed in a thin film over the entire surface. Suitable cleaning solvents include mineral spirits, turpentine, and high-flash naphtha. The manufacturer's recommendations for the use of solvents always should be followed. In certain instances, alkaline detergents such as trisodium phosphate may be used to remove residual oils. Surfaces cleaned with detergents must be thoroughly rinsed with water to remove alkaline residue. The water should be hot or under pressure, preferably both. Some materials may not be easily removed by these solvents and detergents, and stronger solvents such as acetone or methyl ethyl ketone may be required.

(2) Weathered galvanized steel.

(a) During the first few months of weathering, the layer of zinc corrosion products normally present on a weathered surface may be incomplete, depending on atmospheric conditions. During this period, the weathered substrate should be rinsed with clean water to remove soluble zinc salts, and the surface should be treated as newly galvanized material.

(b) When galvanized steel is completely weathered and all the bright zinc surface has changed to a dull surface layer, some paints will perform satisfactorily. The time needed for weathering varies with the local exposure conditions, and it can differ for different parts of a structure. A weathered surface may be difficult to clean completely; therefore, it may be more satisfactory to paint galvanized steel when it is new. Normal weathering produces a finely etched surface that will provide sufficient roughness for painting. Suitable paint will adhere quite satisfactorily to this type of surface, even though the reaction products generally are considered to cause some loss of adhesion. The slight etching of the weathered surface may be the controlling factor.

(c) Just how effective this weathering can be depends on the microstructure of the zinc surface and on stresses in the metal. Careful inspection is necessary to ensure that weathering has produced a dense, uniform, adherent coating. The surface zinc is expected to have under normal conditions contains a mixture of the zinc oxide, zinc carbonate, and basic zinc carbonate hydrates. Some indications suggest that optimum painting results can be obtained if weathering can be continued until iron-zinc alloy layers are exposed.

(d) Weathering will remove entrapped oil and chromates applied for wet storage stain control and allow the patina of adherent corrosion products to form.

(e) For a subsequent paint application, there should be

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some concern about the effect of temperature on this system. Some spalling has occurred at low temperatures, possibly because of incomplete weathering. This condition has been found even in conjunction with a zinc dust/zinc oxide primer that has given excellent results in two-coat systems in a wide variety of tests and services. Careful inspection ensures that weathering has been uniformly effective.

(f) The deliberate use of weathering as a pretreatment method of new zinc surfaces prior to painting is not a preferred practice because the minimum time needed for full weathering cannot be easily assessed and because it is difficult to clean a weathered surface completely (for example, to wash off soluble sulphates). In addition, the recognized pretreatments for painting permit more positive quality control, and the barrier effects of a weathered surface are indeterminate. However, in practice, paint on a weathered galvanized structure has a longer life than a comparable system on black steel.

(3) Brush-off blast cleaning. Galvanized surfaces can be prepared by brush-off blast cleaning. This procedure will etch the surface to enhance adhesion, but it also may remove the galvanizing and thereby defeat its purpose.

(4) Phosphatizing treatments.

(a) Currently, the most common chemical paint pretreatments for zinc-coated steel convert the surface to a nonreactive zinc phosphate. Most effective phosphatizing baths for zinc surfaces are mildly acidic. They contain orthophosphoric acid; zinc phosphate; oxidizing agents such as nitrates or chlorates; and a metallic ion accelerator such as iron, nickel, cobalt copper, or other metals below zinc in the electromotive series. One additional chemical constituent may be necessary to phosphatize zinc-coated steel. The presence of aluminum in quantities of 0.1 to 0.5 percent in hot dip zinc coatings necessitates the use of an additional "accelerator" in the phosphatizing solution. The most common chemical ion for promoting phosphatizing on aluminum-bearing zinc is fluoride or other soluble metal fluorides.

(b) A typical liquid zinc phosphate treatment can be applied by brush, spray, or immersion, preferably after the zinc surface has been exposed by abrasion or etching. After 3 to 6 minutes, the surface should be washed with clean water and allowed to dry before application of the paint. This need for washing down after application makes it difficult to treat large structures, and this treatment should not be used if there is a danger of acid entrapment in joints because of poor rinsing. In this situation, a wash primer is indicated. One gallon of zinc phosphating solution will cover approximately 93 sq m (1,000 sq ft) of zinc surface.

This treatment gives a strongly adherent coating under most conditions because it is formed by a reaction with the zinc surface. It also provides a good mechanical tooth for the paint because of the etching and fine capillary nature of the crystals that are formed. However, painting must take place soon after treatment to avoid pick up of surface contaminants.

(5) Wash primers.

(a) A variation of phosphate conversion coating is available in the form of wash primers. These primers consist of polyvinyl butyral resins to which are added zinc tetroxy chromate pigment and phosphoric acid, as well as certain phenolformaldehyde, cresolformaldehyde, or melamine resins to stabilize the primer or to obtain other film properties. Originally, wash primers came only in two containers that had to be mixed before using. Now, one-container wash primers have been developed. These primers are useful for large structures that will not fit into spray washers or tanks used for phosphate or chromate treatments. They are applied by spray application.

(b) The reactions involved are complex, but the net result is a passivation of the zinc surface, the formation of some zinc phosphate, and conversion of the resin into a relatively insoluble film. Although the range of paints that will adhere well to such films is somewhat smaller than for phosphatizing, a system based on wash primers can give satisfactory service. Their major advantage is that no rinsing is required. The mechanism of bonding is similar to that of the phosphate coating. The presence of pigment and a film-forming vehicle immobilize the zinc phosphate coating as it forms while the film is drying. In this respect, the wash primers are a combination pretreatment and primer.

(c) Wash primers must be applied in a thin coat to achieve good adhesion. The dry film thickness should not exceed 0.013 mm (0.5 mil). This is a potential source of failure, and the fact that the thickness should not exceed 0.013 mm (0.5 mil) should be especially emphasized.

(d) The wash primer should not be applied to a wet surface nor to a previously chromated or phosphatized surface because the reaction will be impeded and the adhesion affected. These wash primers must be primed and topcoated promptly because inherent resistance of wash primer films to moisture is low.

d. Aluminum surfaces.

(1) Maintenance of shop-applied coatings. Coated aluminum usually is covered with a factory-applied coating that has been applied under controlled conditions and baked

to obtain maximum adhesion. These coatings usually are rather thin. However, they are primarily an acrylic or vinyl acrylic, which have excellent weathering resistance. For the most part, aluminum surfaces with this type of coating are recoated or repaired where damage has occurred or when the coating has weathered to the point that a general recoating of the surface is necessary. There is little or no corrosion of the aluminum on these surfaces. Thus, maintenance and repair usually only involve the application of an additional coat (or coats) of a compatible topcoat over the previous coating. In this situation, the required surface preparation primarily involves a thorough washing to remove any chalk, dirt, grease, or other impurity; this step is followed by the recoating procedure.

(2) Aluminum corrosion. Occasionally, coated aluminum surfaces become corroded. The corrosion usually has the appearance of a white aluminum oxide that may form in small pinpoints in and around the break in the coating. On aluminum surfaces—such as those on the aluminum deck houses on ships, particularly where such structures are joined to a steel hull—aluminum corrosion can be extensive and there may be undercutting and considerable pitting of the aluminum surface. When aluminum is corroded, the surface should be abraded, and the abrasion should be light. If blasted, the abrasive used should be very fine, and the nozzle should be held a considerable distance from the surface. Aluminum is a soft metal that both cuts and warps easily.

e. Wood surfaces.

(1) Finish removal. The removal of paint and other film finishes is time consuming and may be a difficult process. However, removal may be necessary when a new surface must be prepared if, for example, the old surface is covered with severely peeled or blistered paint and cross-grain cracking has occurred from excessive paint buildup. This process is also necessary when a penetrating stain or water-repellent finish applied to a previously painted surface is desirable. There are several options for paint removal including sanding, using electrically heated paint removers and blow torches, chemical strippers, and sandblasting or spraying with pressurized water.

(a) Sanding. Disk or siding sanders equipped with a tungsten carbide abrasive disk of medium grit are effective in removing old paint. The method is faster than the others discussed here, and the tungsten carbide disk is less likely to clog than conventional sanding disks. The depth of cut for the sander can be set with the siding guide, but experienced operators often work freehand without the guide. The operator should be careful to remove only paint and not excess wood. After finishing with the disk sander, the surface should be smoothed somewhat by light hand sanding or with a straight-line power sander using 120-grit sandpaper in the direction of the wood grain.

(b) Heat. Electrically heated paint removers can be used to strip paint. The remover simply heats the paint, which causes it to separate from the wood. Although effective, this method is slower than sanding and requires at least a 1,000-watt heater to be effective. An open-flame blowtorch also may be used. A blowtorch is effective and inexpensive, but there is a constant danger of starting a fire within the walls of the building from flames that penetrate cracks in the siding.

(c) Chemical. Liquid paint and varnish removers—such as commercially prepared chemical mixtures, lye, or trisodium phosphate—also will remove paint from wood surfaces. However, the surface sometimes must be neutralized after removing the paint with chemical removers. Before repainting, the wood surface should be sanded in the direction of the grain. Strong caustic solutions, such as lye and trisodium phosphate, leave the wood surface extremely porous.

(d) Sandblasting and pressurized water spray. Blasting with sand or high pressure water also can be used to remove paint; however, these methods usually require the services of a professional. The sand particles or water can erode the wood as well as strip the paint. The softer earlywood is eroded faster than the latewood; this results in an uneven, rough surface that may not be suitable for painting. Approximately 4,134 to 13,780 kPa (600 to 2,000 psi) of pressure is used with water.

Chapter 8 Coating Application

8-1. Introduction

a. Transferring coating materials from the can to the substrate can be accomplished in several ways. Application methods can range from simple brush and roller to sophisticated spraying. All application methods have inherent advantages and limitations.

b. The choice of an application method depends on the type of coating to be applied, the type and size of surface to be coated, and governing environmental regulations. Contracts will either specify the application method to be used or will permit the contractor to choose a method. However, the consistency of some coatings may dictate a particular method. For example, coatings that are excessively viscous may not permit effective application by spray; or a low viscous coating may only be effectively applied by spray. Either the specifications or the manufacturer's instructions usually will indicate the preferred application method.

8-2. Methods of Coating Application

There are various methods of coating application, including brush application, roller application, conventional spray, high volume-low pressure spray, airless spray, plural component spray, and electrostatic spray. The technologies, techniques, advantages and limitations, equipment, typical coating types involved, and safety considerations for each type of application method will be discussed.

a. Brush application.

(1) There are a variety of brush sizes, shapes, bristle types, and uses. The brush most commonly used for structural steel and similar substrate applications is the conventional wall brush. Oval brushes are commonly used for structural and marine applications, particularly around irregular surfaces such as rivets, boltheads, piping, railing, and similar areas. Widths for the conventional wall brush vary from 25.4 to 152.4 mm (1 to 6 in.), but the most commonly used size is 101.62 mm (4 in.) The two types of bristles used in brush assemblies are synthetic (nylon) fibers and natural (hog) bristle fibers. Synthetic bristles have excellent abrasion resistance when coatings are applied to rough, uneven steel; concrete; and masonry surfaces. Although not affected by most solvents, coatings containing such strong solvents as ketones may affect the synthetic fibers. Natural (hog) bristles, although more expensive and water sensitive, provide the best leveling application

characteristics and strong solvent resistance. Proper brush and bristle selection for a specific coating application is imperative for a quality application.

(2) Good brush loading and coating distribution techniques will provide an even application free of laps, runs, drips, and other unacceptable finish characteristics. The brush should be held lightly but firmly, and the paint should be spread over the surface with moderate, even pressure by stroking in one direction, followed by stroking at right angles to the previous coat.

(3) An advantage of brush application is the ability to stripe coat. In many instances, brushing difficult areas (e.g., edges, rivets, corners, boltheads, and welds) prior to the application of a general spray coat is recommended; this process is known as striping. Striping is performed to assure adequate coverage and thickness of the applied coating for areas that are difficult to coat properly by general spray application alone. However, brushing, including brush striping, is not recommended for application of vinyl zinc-rich and epoxy zinc-rich coatings because the zinc must be kept in suspension during application. This is accomplished using agitators in the spray pot or pump. Another advantage of brush application is that it aids in thorough wetting of the substrate, particularly on surfaces that are porous.

(4) Limitations of brush application are that it is slow and tedious, and it may not produce a uniform coating thickness. Brush application of a coating is not practical for large surfaces, and it may leave unsightly brush marks with coatings that do not level well. Brush application of certain coatings, such as high-solids and fast-drying coatings, is difficult and generally is not recommended.

(5) Oil-based and waterborne coatings typically are the most common coating types applied by brush, and their application characteristics are considered good to excellent. The oil-based, slow-drying paint should be brushed out thoroughly to work the coating into cracks, crevices, or other irregular surfaces. Faster drying paints (waterborne) should be brushed out quickly and evenly; otherwise, overbrushing will leave brush marks as the paint dries.

b. Roller application.

(1) The roller assembly consists of a cover and core. Roller covers vary in diameter, length, type of fabric, and fiber length (nap). The 38.1-mm (1-1/2-in.) diameter and 228.6-mm (9-in.) length is the most common size. Polyester, nylon, mohair, and lambskin are typical cover fabrics. Selection of fabric and fiber length depends on the type of coating and the condition of the surface. Woven

fabrics shed fewer lint particles, so they typically are designated for all coatings, especially gloss coating. In addition, longer fibers hold more coating, but they do not provide as smooth a finish. The length of fiber used on steel surfaces varies from 6.35 to 19.05 mm (1/4 to 3/4 in.). Additionally, the roller core must be resistant to strong solvents when applying epoxies, vinyls, urethanes, and similar materials. There are three special types of rollers, including the pipe roller, fence roller, and pressure roller.

(a) The pipe roller is constructed of two to five narrow rollers on a single spring spindle. The rollers readily conform to contoured surfaces, such as piping. The size of the pipe determines the number of segments required, and the threaded handle accommodates the use of an extension pole.

(b) Fence rollers require roller covers with extra long nap (31.75 mm [1-1/4 in.]). These covers enable rapid coating of wire fence from one side because the long nap surrounds the fence wire and coats it on both sides concurrently.

(c) A pressure roller permits continuous coating by steadily supplying coating from a pressurized tank to directly inside the roller. The roller cover is made of a perforated core that enables a coating to pass from inside the roller to the nap. The valve that controls the pressure is located on either the roller handle or the tank.

(2) The roller should be uniformly loaded with paint to provide even application. Skipping will occur when paint is inadequately loaded onto the roller. However, tracking will occur if an excessive amount of paint is loaded onto the roller. Proper application pressure and technique should be used; initially, a zigzag overlapping application should be performed followed by a second coat applied at right angles to the first coat.

(3) Rollers are excellent for large, flat areas (e.g., tank sidewalls and tops, decks, ship hulls, walls, and ceilings) or whenever application does not require the skill needed for brush or spray application. Rollers also are recommended for use in windy conditions to eliminate excessive material loss and overspray. Rollers may be used for indoor application when overspray cannot be tolerated. Roller application on concrete cracks and voids is difficult because of the shape of the roller; therefore, a brush is recommended to work the coating into these areas. Roller application is more rapid than brush application but slower than spray application. A roller generally holds more coating than a brush, and it will provide a more satisfactory finish on smooth surfaces compared with rough or irregular surfaces. Brush or spray application is the preferred method for rough or irregular surfaces.

(4) Roller application characteristics for oil-based and waterborne coatings are excellent, and epoxies and urethanes are considered to be fair to good. Roller application characteristics for high solids coatings and inorganic zinc-rich coatings are considered poor. High performance coatings/linings for immersion are seldom applied by roller because of nonuniform thickness and wicking caused by roller nap residue.

c. Conventional spray application.

(1) Equipment. The conventional method of spraying relies on air for coating atomization. Jets of compressed air introduced into the stream of coating at the nozzle break the coating into tiny droplets that are carried to the surface by the current of air. The transfer efficiency is estimated to be 25 to 30 percent. A typical, conventional spray setup consists of: air compressor, oil and water extractor (separation), pressure feed tank (pressure pot) or paint pump, connecting hoses, and spray gun.

(a) Although the pot regulates both the air and fluid pressures fed to the spray gun, the air compressor generates the necessary pressure for these two flow operations. Air compressors can be of various types, and the size usually depends on the amount of air required in cubic feet per minute to operate the spray gun. Hoses must be properly sized to deliver the right amount of air volume and pressure to the spray gun. Approximately 275.6 to 413.4 kPa (40 to 60 psi) and 4.012 liters/sec (8.5 cfm) are needed to operate most production conventional spray guns with a medium viscosity coating such as latex paints, some lacquers, stains, sealers, alkyds, and conventional epoxies such as those specified in MIL-P-24441A.

(b) A separator should be in line, between the air compressor and the pressure pot, to prevent moisture and oil from reaching the coating. Moisture/oil separation for conventional spray should be considered mandatory. The use of properly sized and maintained moisture and oil separators helps ensure the quality of the finished product. In addition to adhesion defects, oil or moisture in the compressed air will mix with the coating during atomization and create voids, pinholes, and/or fisheyes in the applied film. A blotter test should be conducted at the spray gun prior to application to ensure a clean, dry supply of atomized air.

(c) The amount of fluid material delivered to the spray gun is controlled by the fluid pressure regulator of the feed tank pressure pot, which is a double regulator type. The pressure pot should be 19 or 38 liters (5 or 10 gallons) in size for most jobs. For the application of certain coatings such as zinc-rich coatings, the pot should be equipped with a mechanical agitator to keep the zinc-rich coating in

suspension so the zinc does not settle on the bottom of the pot. If application stops and resumes after 15 minutes when spraying zinc-rich coatings, the entire length of the hose should be whipped to redisperse the coating in the line. If more than 1 hour has passed, all the coating in the line should be blown back into the pot and reagitated prior to use. The mixing and straining of paints are covered in Chapter 9. When coating tall structures, the pot should be kept at nearly the same level as the spray gun so lower pot pressures (55.12 to 82.68 kPa [8 to 12 psi]) can be used. Longer hoses and higher pot pressures are required when the pot is not at the work level. Excessive fluid pressure may cause the fluid stream to exit the fluid nozzle at a higher velocity than the air jets in the air nozzle can properly atomize. When the pot is not placed at or near the work level, the lower pot pressures can be maintained by using a fluid pump to pump the coating from the pot to the gun. These pumps are commonly used with hot spray setups.

(d) Two types of hoses are used in conventional spray coating: the air hose and the fluid hose. The air hose (supply line) from the compressor to the pot typically is red and usually is 19 to 25 mm (3/4 to 1 in.) i.d. The air hose from the pot to the spray gun also is red and should be 6.35- to 7.9-mm (1/4- to 5/16-in.) i.d. and as short as possible. The fluid hose usually is black and has a solvent-resistant liner. The inside diameter should be 7.9 to 9.5 mm (5/16 to 3/8 in.) for medium viscosity materials and also should be as short as possible. Hoses up to 12.7-mm (1/2-in.) i.d. are commonly used. Excessive hose length allows the solids to settle in the line prior to reaching the spray gun. This leads to clogging and the application of a nonhomogeneous film.

(2) Conventional hot spray. Conventional hot spray is similar to the standard conventional spray and is used during cooler temperatures to lower viscosity of the paint without having to add additional thinners. This reduction in paint viscosity is achieved by heating the coating to 66 to 71 °C (150 to 160 °F). The paint is hot when it leaves the spray gun, but the atomizing air cools the paint and evaporates the solvents. When the paint reaches the surface, it usually is only a few degrees warmer than if it was not heated. This process also provides less overspray because the material can be atomized at lower pressures. The hot spray process eliminates the need for additional thinners for application at colder temperatures. Excessive thinners reduce film buildup and cause solvent popping (craters) and orange peel. The equipment used in this process, in addition to the typical equipment, involves a heater and a hose from the heater to the spray gun; therefore, two material hoses are required. Hot spray application generally is restricted to the shop. Application without heating is used in the field because all types of paints can be used, including catalyzed paints.

These catalyzed coatings cannot be used with the hot spray method because the heat will cause the coatings to set up in the equipment.

(3) Spray gun and adjustments. By varying the volume of air and coating at the spray gun, the amount of atomized coating can be regulated. The selection of a fluid nozzle and needle size is another way to regulate the amount of coating exiting the fluid nozzle. Excessive amounts of coating flowing through the fluid nozzle at low pressures (55.12 to 82.68 kPa [8 to 12 psi]) can be reduced by adjusting the material flow knob on the gun. Alternatively, a smaller fluid nozzle/needle combination may be used. Coating manufacturers normally recommend at least one set of sizes known to work for their product. The air nozzle cap can be for either internal mix or external mix. The internal mix involves mixing of the coating and air inside the spray nozzle. The external mix involves mixing of air and paint outside the nozzle between the horns. The most common method is the external mix because it produces a fine atomization and, if properly controlled, will provide the best quality finish. Internal mix nozzles do not provide the same quality finish as the external mix, and they are not recommended for fast-dry-type coatings (lacquer) because the coating tends to clog the nozzle tip, which results in distorted spray patterns. With both types, the atomized air breaks the streams into tiny paint droplets and provides the velocity for the coating to reach the surface. The pattern of the spray (round or oval) is determined primarily by the air adjustments on the gun and the air cap design. The needle valve regulates the amount of coating material that flows through the fluid nozzle. The distance that the needle can be withdrawn from the fluid nozzle is controlled by the fluid control knob on the back of the spray gun. The air valve is operated by the gun trigger. When the trigger is pulled, the air flow begins then the fluid flow follows. This is a major advantage of conventional (air) spray. By half-triggering the gun, the atomized air flows (without coating). This airstream is used to remove dust and loose debris from the surface prior to the coating application. The trigger is fully depressed to apply the coating.

(4) Spray application techniques.

(a) After the fluid and air pressures are properly adjusted, several basic spray techniques should be used to ensure the application of a consistent film of coating. A spray pattern 203.2 to 254 mm (8 to 10 in.) wide should be created by adjusting the air pattern control knob. The spray gun should be held at right angles to the work surface. "Arcing" the gun or flipping the wrist at each end of a pass results in a nonuniform coating film and excessive overspray.

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(b) For large flat areas, each stroke should overlap the previous one by 50 percent. This produces a more uniform coating thickness. The stroke length may vary from 457.2 to 914.4 mm (18 to 36 in.), depending on the sprayer's arm length. To build a uniform coating thickness, a cross-hatch technique is usually used. The cross-hatch spray technique consists of a wet spray coat, using 50 percent overlap, followed by another full wet spray coat at right angles to the first.

(c) The spray gun trigger should be released at the end of each pass. At the beginning of a pass, the gun should be in motion prior to pulling back on the spray gun trigger and continued briefly after releasing the trigger at the end of the stroke. This produces a uniform, continuous film. Proper triggering also reduces coating loss; prevents heavy buildup of coating at corners, edges, and ends of strokes; eliminates buildup of fluid on the nozzle and tip; and prevents runs and sags at the start of each stroke.

(d) Proper spray techniques, which are necessary to produce a quality coating application, typically are acquired with experience. Quality coating application also depends on proper thinning of the coating, correct fluid pressure, and proper fluid nozzle size. Using proper techniques, a uniform coating thickness should be attained. Most types of paints, including epoxies and vinyls, can be effectively applied with a nozzle orifice size of 0.070 in. When spraying normal viscosity coatings, the orifice size generally should not exceed 0.070 in. because flooding may occur. Coal tar epoxies can be applied effectively using a 0.086-in. nozzle orifice.

(e) The proper gun-to-surface distance for a uniform wet film generally varies from 203.2 to 254 mm (8 to 10 in.) for conventional spray (compared to 12 to 18 in. for airless spray). If the spray gun is held too close to the surface, the gun must be readjusted or heavy coating application with sags and runs will occur. If the spray gun is held too far from the surface, dry spray will result and cause holidays or microscopic pores in the coating.

(f) Striping by spray also can be performed. A good practice is to apply an extra spray pass (stripe coat) prior to the first general spray coat not only on the edges but also on corners, interior angles, seams, crevices, junctions of joint members, rivets, weld lines, and similar irregular surfaces. This technique will assure adequate film buildup within complex, irregular areas. A full cross-hatch spray coat is applied after this striping.

(5) Advantages. Spray application of coatings is a highly efficient method of applying high performance coating systems to a substrate, and it results in a smoother, more uniform surface than obtained by brushing or rolling

because these application methods tend to leave brush or stipple marks and result in irregular thicknesses. Large amounts of material can be applied in very short periods of time with spray application compared to brush and roller application. The ability to independently vary fluid and air gives conventional spray the ability to provide a wide selection of pattern shapes and coating wetness by infinitely varying the atomization at the gun. Conventional spray application has a high degree of versatility and relies on a combination of air caps and fluid nozzles available for different coatings. Spray gun triggering is more easily controlled for precise spraying of irregular shapes, corners, and pipes than with airless spray. The spray gun also can be used to blow off dust from the surface with compressed air prior to applying the coating. Conventional spraying provides a finer degree of atomization and a higher quality surface finish necessary for vinyl applications.

(6) Limitations. Because larger amounts of air are mixed with the coating during application using conventional spray, coating losses from "bounce back" or "overspray material" that miss the substrate can be high, depending on the configuration of the substrate. This bounce back effect makes coating corners and crevices difficult. Conventional spray also is slower than airless spray application.

(7) Coating types. Most industrial coating materials can be applied using a conventional spray. Fluid tips with various orifice sizes can be used effectively with epoxies, vinyls, and coal tar epoxies. Larger size tips can be selected for more viscous, mastic-type coatings. The coating manufacturer often recommends application equipment and will specify tip sizes for optimum application characteristics.

(8) Equipment care. When coating application is completed, all equipment components should be thoroughly cleaned. To properly care for the spray application equipment, the gun, hoses, and auxiliary equipment should be flushed thoroughly with an appropriate solvent after each use; otherwise, dried/cured coating materials will accumulate and cause the equipment to become inoperable. Thinner or a suitable solvent should be run through the tank, hose, and gun until the solvent runs clean with no visible coating color. All pressure should be released from the tank, line, and gun; and the gun should be disconnected from the line and disassembled. All components should be thoroughly cleaned with solvent, air blown, and reassembled for future use. The exterior surface of the gun should be wiped down with solvent-dampened rags.

(9) Safety considerations. Only recommended pressure and equipment should be used for conventional spray. Also, hose fittings should never be loosened while under pressure.

d. *High volume-low pressure spraying.* A high volume-low pressure (HVLP) setup consists of a high volume air source (turbine generator or compressed air), a material supply system, and an HVLP spray gun. The spray techniques associated with HVLP are closely compared to that of conventional spray and are a growing trend in coating application techniques. HVLP uses approximately the same volume of air as conventional spray, but lower pressures are used to atomize the fluid. Reducing air pressure at the nozzle effectively reduces the velocity of the airstream and atomized fluid. This reduces the bounce back of coating material from the surface, which results in a significantly higher transfer efficiency (55 to 70 percent) and application into recessed areas. The high transfer efficiency attained reduces material costs and waste, and an HVLP spray is easy to set up and simple to operate. However, HVLP spray has a lower production rate than airless spray; and some coatings are difficult to atomize, which can limit the use of HVLP spray.

e. *Airless spray.*

(1) Equipment. Airless spray equipment consists of a power source (an electric motor or air compressor), an air hose and siphon hose, a high pressure fluid pump with air regulator (if a compressor is used), a fluid filter, a high pressure fluid hose, and an airless spray gun with spray tip and safety tip extension. Each of these components will be discussed.

(a) The power source may consist of either an electric motor or an air compressor. An electric motor may be used to drive the fluid pump. The electric airless is a self-contained spray outfit mounted on wheels that operates on 120-V electrical power. Conversely, a remote air compressor can be used to drive the fluid pump. The larger, air-operated units are more commonly used on large USACE structures, and the smaller mobile units are used on small projects. The larger units are required to operate multiple pumps or other air-driven devices; they also provide the larger air supplies necessary to apply mastics and high-build coatings.

(b) A 12.7-mm (1/2-in.) air hose generally is used to deliver air from the compressor to the pump. The most common hose length is 50 ft. However, as hose length and pump size increase, a larger diameter hose should be used.

(c) The material siphon hose should be 12.7- to 19.05-mm (1/2- to 3/4-in.) i.d. to provide adequate fluid delivery. The hose must be resistant to the solvent and coating being used. A paint filter, often with the spray gun, should be used to prevent dirt or other contaminants—including improperly dispersed pigment (slugs)—

from clogging the tip. In some instances the siphon hose is eliminated and the pump is immersed directly into the paint. This is known as a submersible airless pump.

(d) The fluid pump is the most important part of the hydraulic airless system. The fluid pump multiplies the air input pressure to deliver material at pressures up to 31,005 kPa (4,500 psi). A common airless pump has an output-to-input pressure ratio of 30:1; that is, for every pound of input pressure, the pump provides 30 lb of output pressure; therefore, this unit will deliver 20,670 kPa (3,000 lb/in.) of hydraulic pressure with 689 kPa (100 psi) of air pressure. Other pumps with a ratio of 45:1 provide pressures up to 31,005 kPa (4,500 psi) (689 kPa [100 psi] input). Air-operated pumps can produce material output ranging from 793.8 g (28 oz) per minute (one spray gun) up to 11.34 liters (3 gallons) per minute (three to four spray guns).

(e) A double-action, airless pump incorporates an air motor piston, which reciprocates by alternate application of air pressure on the top then the bottom of the piston. The air motor piston is connected directly to the fluid pump by a connecting rod. The fluid section, or pump, delivers fluid on both the up and down strokes.

(f) The high pressure fluid hose is manufactured to safely withstand high fluid operating pressures. The hose typically is constructed of vinyl-covered, reinforced nylon braid and can withstand pressures up to 31,005 kPa (4,500 psi); therefore, it is important not to bend the hose or restrict the material flow in any way or the hose may rupture. The hose also is constructed to resist strong solvents. A wire may be molded into the hose assembly to prevent a possible static electrical charge. The spray gun should be equipped with a high pressure swivel to accommodate any twisting action of the hose. The inside diameter of the hose should be at least 1/4 in. for most common coatings, except the viscous mastic-type coatings. The hose should not be longer than necessary; however, this is not as critical as for conventional spray. High pressure hose diameters up to 12.7 mm (1/2 in.) are used for more viscous mastic-type coatings.

(g) The airless spray gun is designed for use with high fluid pressures. The airless spray gun is similar to a conventional spray gun in appearance, but it has only a single hose for the fluid. The hose may be attached to the front of the spray gun or to the handle. The resulting airless spray (atomization) occurs when fluid is forced through the small orifice of the fluid tip at high pressures.

(2) Airless hot spray. An airless hot spray can be used to apply coatings at higher temperatures to reduce viscosity

without additional thinners. Equipment is similar to that used in the standard airless spray setup, except that a unit to heat the material is required.

(3) Tip size nomenclature. A variety of airless spray tips are available. Tip selection is based on the type of material being sprayed and the size of spray pattern desired. The tip orifice opening and the fan angle control the pattern size and fluid flow. There are no controls on the spray gun itself. Tip orifices vary in size to accommodate the viscosity of the coating being applied. Fan angles range from 10 degrees (101.6 mm [4 in.] spray width) to 95 degrees (431.8 mm [17 in.] spray width). For example, two nozzle tips with the same size orifice but with different spray angles will deliver the same amount of coating over a different area width. For example, two tips with an identical orifice size of 0.381 mm (0.015 in.) but different spray angles (10 and 40 degrees) will provide fan widths of 101.6 and 215.9 mm [4 and 8-1/2 in.], respectively, and will have identical flow rates of 0.0145 liters/sec (0.23 gallons per minute) at 13,780 kPa (2000 psi). Typically, when spraying a dam gate with an epoxy using a 0.381-mm (0.015-in.) orifice tip, fan angles ranging from 10 degrees (101.6 mm [4 in.]) to 50 degrees (254 mm [10 in.]) would be used. The quantity of sprayed coating is determined by the orifice size of the spray tip. A larger orifice results in more fluid being delivered at a faster speed; however, this leads to poorer atomization. Dual or adjustable tips can be used with airless spray equipment. Dual tips frequently are ball tips with two separate orifices. This feature provides the sprayer with the option of two different spray patterns: a narrow fan for smaller surfaces and a wide fan for production spraying. Adjustable tips vary the spray fan and, simultaneously, the tip orifice. The tip size increases as the fan width increases.

(4) Airless spray techniques. Application techniques for airless spray are similar to those for conventional spray, except that the spray gun should be held 304.8 to 457.2 mm (12 to 18 in.) from the surface as opposed to 203.2 to 254 mm (8 to 10 in.) for conventional spray because of the increase in the amount of coating being applied.

(5) Advantages. Airless spray equipment provides higher film buildup capabilities, greater surface penetration, and rapid coverage; it can handle products formulated with higher viscosity without the addition of large quantities of solvents; and it has low pressure loss when the pump is not at the same level as the actual spraying. Also, the single hose can be longer than a conventional sprayer and easier to handle. Mastic-type coatings such as coal tar epoxies (CTEs) are easily atomized by airless spray equipment. When spraying concrete and other masonry surfaces, airless spray efficiently and easily penetrates voids and general porous surfaces. Hydraulic pressure is used to force coating

through an orifice in the spray nozzle. The high degree of pressure atomizes the coating as it is discharged through the spray nozzle without the need for atomized air. The coating beads into small droplets when released under these pressures (2,756 to 31,005 kPa [400 to 4,500 psi]) and results in a finely atomized spray and a transfer efficiency of 30 to 50 percent. Typical pressure for epoxies such as those specified in MIL-P-24441A are 12,402 to 17,225 kPa (1,800 to 2,500 psi), and 19,292 to 20,670 kPa (2,800 to 3,000 psi) for high solid epoxy mastics. Because of the high fluid pressure of airless spray, coatings can be applied more rapidly and at greater film buildup than with a conventional sprayer. The high pressure coating stream generated by an airless spray will penetrate cavities (which are typical on lightweight concrete blocks) and corners with little surface rebound.

(6) Limitations. Variances of the structure being painted in the field may create problems because of the difficulty in changing spray fan patterns and orifice openings in the field. For example, when spraying a large structure, a wide fan width will work well and provide the desired finish; however, when a complex design of a small surface area is encountered (e.g., back-to-back angles and other attachments) a small fan width is necessary to provide a quality finish. Because an airless sprayer does not atomize coatings as well as a conventional sprayer, it should not be used for detail or fine finish work. Additionally, if painters use excessive pressure or improper technique, solvent entrapment, voids, runs, sags, pinholes, and wrinkles may occur.

(7) Safety considerations. The spray gun should never be removed from the hose, or the tip from the gun, until the pressure from the pump and in the line has been released. High pressure through a small orifice can cause paint to penetrate the skin if pressed against the body; therefore, spray gun tips are equipped with trigger locks and tip guards. All high pressure airless systems should be sprayed and flushed in a well ventilated area. These systems also should be grounded to avoid dangerous static sparking, explosion, or fire when spraying or flushing the lines. (See Chapter 10 for a more detailed description of recommended safety practices.)

f. Air-assisted airless spray. The air-assisted airless sprayer was developed to combine some of the advantages of an airless sprayer (e.g., increased production, ability to reach into recesses and cavities without blow-back) and the advantages of a conventional sprayer (finer atomization). An air-assisted airless spray system consists of a spray gun, pump, hoses, and clean, compressed air of adequate pressure and volume. An air-assisted airless sprayer may be used with small containers or with 207.9-liter (55-gallon) drums

using a submersible pump. Basically, an air-assisted airless spray gun combines the features found with both air and airless spray guns. A special fluid nozzle tip similar to that used with the atomization principle of the airless sprayer initiates atomization. Atomization is completed with the introduction of compressed air through the horns and face of an air cap (similar to a conventional spray air cap) that surrounds the airless tip. Without the compressed air, a coarsely atomized and poorly defined pattern would result. The compressed air emitted from the air cap provides a finely atomized coating, which approaches the quality of conventional spray atomization. Therefore, an air-assisted airless sprayer is ideally suited for fillers, glazes, lacquers, and polyurethanes. Medium to heavy consistency coatings require atomizing air pressure close to 68.9 kPa (10 psi). Light consistency coatings only require a few pounds per square inch of air pressure. Equipment maintenance and safety considerations are similar to those for standard airless and conventional spray equipment.

g. Plural component spray application.

(1) Perhaps the most complex of all spray application methods is plural component spraying. Basically, plural component spray mixes the individual components through careful metering at the spray gun or at the spray tip rather than premixing in the pressure pot. Plural component spray is commonly used for 100 percent solids coating materials and coating materials with limited potlife (such as epoxies).

(2) A plural component spray setup consists of six basic components: proportioning pump, mix manifold, mixer, spray gun, material supply containers, and solvent purge (flush) container. Plural component spray can be sprayed by conventional spray, airless spray, or air-assisted airless spray. The spray gun can be identical to those used with conventional sprayers, airless sprayers, or electrostatic sprayers. However, if the components are mixed at the gun, a special spray gun is required.

(3) Three systems are used to spray polyester materials, including a side catalyst injector system, an air injection system, and a split batch or double nozzle spray system. The side catalyst injector system mixes the polyester components externally in front of the spray gun. With an air injection system, a measured quantity of catalyst is injected into the atomizing air supply. The split batch or double nozzle spray gun system involves two quantities of equal volumes of premixed resin. The two quantities, in equal volumes, are delivered separately to the spray gun and are atomized in such a way that the individual quantities are intimately intermixed either externally or internally.

(4) Some types of plural component coating materials or

adhesives that can be sprayed include polyesters, polyurethanes, vinyl esters, and epoxies. These materials may be mixed in varying ratios and viscosities.

(5) The application technique associated with plural component sprayers essentially is no different than that of conventional air or airless sprayers. However, the prespray procedures require a certain level of expertise in ensuring proper mixing of the individual components and equipment maintenance.

(6) Unlike conventional or airless sprayers, plural component sprayers combine separate fluids that are either mixed internally immediately preceding exit from the gun or externally; therefore, plural component spraying is the ideal system to use with coatings that have a short pot life (i.e., 30 minutes).

(7) A plural component spray setup uses complicated equipment compared to that used in conventional or airless sprayers. Because of the knowledge necessary to successfully apply coatings using plural component sprayers, a more experienced applicator generally is required.

(8) Whenever the equipment is stored, even for a short period of time, it must be cleaned thoroughly; different procedures may be required for overnight versus weekend storage. The system must be kept "wet" (filled with solvent) at all times to prevent the remaining material from setting up when it is exposed to the atmosphere. A solvent that is compatible with the resin materials should be used.

h. Electrostatic spray.

(1) There are several types of electrostatic spray systems, although the typical system involves hand-operated, electrostatic spray guns using air atomization, airless atomization, or air-assisted airless atomization. The equipment used to atomize the coating is similar to that of conventional, airless, or air-assisted spray setups; however, an electrostatic, high voltage supply also is used.

(2) Portable electrostatic spray units are used for coating applications to odd-shaped metal objects, such as wire fencing, angles, channels, cables, and piping. Electrostatic spray units impart an electrostatic charge to the coating, which causes the material to be attracted to a properly grounded object. The charged coating particles travel to the closest grounded object. The particles that miss the target wrap around to coat the opposite side of the target. Particles that strike the product and rebound are retracted to the surface.

(3) Virtually any atomized fluid is capable of accepting

an electrostatic charge. Careful consideration must be given to the type of electrostatic system being used. Each system demands paint formulation consideration acceptable to the process being used. Polar solvents (conductive) are required to improve the degree of atomization.

(4) The advantages to using electrostatic spray include: this method of coating application reduces coating material loss as it utilizes overspray by rebound; it reduces cleanup and maintenance time, increases production rates, and reduces the number of application steps caused by wrap-around; and it results in improved atomization.

(5) The uniformity of coverage will vary depending on the size and contour of the object. Because of the electric field, the exterior corners of items being coated often receive a heavier coating; the interior corners are difficult to coat. Also, coating materials may require special formulation, such as adding special solvents to the coating, to enable it to accept the charge. The item(s) to be sprayed must be grounded at all times. Electrostatic spray guns are limited to the amount of fluid they can efficiently charge in a given period of time. Observing safe operating procedures is extremely important because of spark potential.

Chapter 9 Coatings Inspection

9-1. Introduction

a. Approximately 85 percent of all premature coating failures are a result of poor surface preparation, inadequate mixing, thinning, and/or poor coating application. Onsite quality control inspection during surface preparation and coating application procedures can help prevent failures of these types. Proper inspection techniques must be combined with knowledgeable instrument use, good common sense, and thorough documentation of work activities and inspection checkpoints to help ensure specification compliance.

b. Paint covers a multitude of mistakes. Without a form of onsite quality control, determining the cause of a problem can be difficult: was the surface properly prepared, were the coating materials properly mixed and applied, or was work conducted when weather conditions were satisfactory? Coatings inspection can increase the life of a coating system by reducing the number of shortcuts taken by the painter.

c. Throughout this chapter, the term "inspector" is used to indicate an individual or a group of individuals whose job is to witness and document surface preparation and coating work in a formal fashion. The inspector's responsibility is to ensure that the requirements of the coating specification are met. This is accomplished by providing job documentation, including a commentary on the type and adequacy of equipment at the jobsite, the rate of work progression, information regarding ambient conditions and controls, and verification that the surface preparation, coating application, coating thickness, and curing are as required. This is supplemented with any other information deemed of consequence to the quality and progress of the work. (Paragraph 9-2 discusses the aspects and importance of documentation.)

d. The amount of inspection and the specific inspection checkpoints will vary with the type and size of the coating project. Eleven quality control inspection procedures are discussed in this chapter:

- Presurface preparation inspection.
- Ambient conditions.
- Compressed air cleanliness.
- Surface profile.
- Surface cleanliness.
- Paint storage, mixing, and thinning procedures.
- Application techniques.

- Wet and dry coating thickness.
- Pinhole detection.
- Adhesion.
- Cure.

USACERL has developed a series of videotapes designed to educate the USACE inspector in quality assurance inspection. This series includes mixing, thinning, and application of epoxy coatings in documentation; safety in painting; evaluation of containment structures; and evaluation of applied coatings.

9-2. Documentation

a. Simply performing quality assurance inspection during blast-cleaning and coating-application operations is not sufficient. The documentation of the results of these procedures provides a permanent record of contract compliance. Proper, thorough documentation has a twofold purpose. The first is the need for historical recordkeeping of the blast-cleaning and coating-application operations performed on USACE structures. Future maintenance painting operations often rely on thorough historical records that document the coating systems applied to a structure and any difficulties encountered. These records often reveal why a coating exhibited an early failure or unusual performance.

b. Another purpose for thorough documentation is to counter any legal claims brought on by the contractor. Litigation has become commonplace in industry, and the protective coatings industry is not excluded from this trend. Thorough documentation of each step throughout the coatings process, including presurface preparation, ambient conditions, surface profile and cleanliness, wet and dry film thicknesses, adhesion testing, cure, and holiday testing, will help to prove or disprove allegations that may arise in a contract dispute. The USACE has been involved in several legal claims that could have been avoided if sufficient documentation was maintained.

c. "Proper" documentation can take many forms. When common inspection instruments are used, industry standards, including those of the American Society of Testing and Materials (ASTM) or Steel Structures Painting Council (SSPC), often have written methods stating how to test, how frequently to test, and how often to calibrate the equipment. These standards should be followed, especially if contract noncompliance or a potential source for a legal claim is encountered or anticipated. Good documentation is not just written. Today's advances in photography and video enable the USACE inspector to permanently capture the progress and quality of a project on film. Documentation of this type may cause the contractor to be more aware of the concern

over quality, and it can be an invaluable source during litigation.

d. The role of a USACE inspector involves precise and thorough documentation of each inspection in the coatings process. Although not all the quality checkpoints are enforceable on every project, the results of the inspection should be documented. However, in reality, a full-time inspector may not be available due to limited staff and multiple contracts to be administered. Work which is inspected though should be carefully documented.

e. The USACE should clearly identify any discrepancies, irregularities, or unusual occurrences that may lead to premature coating failure. This information will assist in preparing for future coating operations through the preparation of historical records. USACE inspectors should maintain a commentary on work progress as it relates to the project, and they should maintain a chronologically organized record book for each project. This record book can be an invaluable reference if a coating problem or legal claim occurs. Maintaining daily documentation of this type is a critical responsibility of a USACE inspector.

9-3. Presurface Preparation Inspection

a. Prior to starting surface preparation and coating work, it is necessary to determine that the structure is ready for surface preparation and painting. Heavy deposits of grease, oil, dust, dirt, and other contaminants may be redistributed by the blast-cleaning process if they are not removed. Removal procedures are detailed in SSPC-SP 1. The requirements of SSPC-SP 1 are included (by reference) in all SSPC hand-tool and power-tool cleaning specifications including SSPC-SP 2, -SP 3, and -SP 11, and in all abrasive blast-cleaning specifications including SSPC-SP 5, -SP 6, -SP 7, and -SP 10.

b. The specifications may require that weld spatter be removed and sharp edges be rounded (customarily to a 3.18-mm [1/8-in.] radius). Unusual pitting in the steel substrate may require grinding, filling, etc. before blast cleaning. Large-scale repairs of this type, however, can be quite costly and time consuming. A judgment should be made (by a qualified structural engineer) to determine the consequences of bypassing pitting repair procedures. Adjacent areas not required to be cleaned or coated should be masked to protect them from the cleaning and coating operations. Presurface preparation procedures are discussed more thoroughly in Chapter 7.

9-4. Measurement of Ambient Conditions

a. Measuring ambient conditions entails obtaining an air

temperature, surface temperature, percent relative humidity, and dew point temperature. The Civil Works Guide Specifications (CWGS) as well as coating manufacturers have pre-established air temperature and relative humidity ranges outside of which the coating materials should not be applied. The ambient conditions must be obtained, documented, and compared with the established ranges for compliance with the governing specifications. Other ambient conditions affecting painting operations include the potential for industrial or chemical airborne contamination.

b. Many ambient conditions are inspected visually. But air temperature, relative humidity, and dew point are determined by instrumentation, including psychrometers or instruments that give direct read-out recordings of humidity or dew point. Measurements with these instruments are taken before work begins each day and periodically throughout the day. A suggested minimum frequency is every 4 hours, but the readings can be more often if weather conditions appear to be changing.

c. Dew point is the temperature at which moisture will condense. Dew point is important in coating work because moisture condensation on the surface will cause freshly blast-cleaned steel to rust or a thin, often invisible film of moisture to be trapped between coats that may cause premature coating failure (blistering). Accordingly, the industry has established an arbitrary dew point/surface temperature safety factor. Final blast cleaning and coating application should not take place unless the surface temperature is at least 3 °C (34 °F) higher than the dew point temperature. Although theoretically a surface temperature just infinitesimally above the dew point will not permit moisture condensation, the safety factor of 3 °C (34 °F) was established to allow for possible instrument inaccuracies or different locations where readings are taken. For example, thicker steel retains temperature and cold longer, and steel in contact with soil or water remains colder.

d. Various field instruments are used for determining surface temperature. One of the most common is a surface temperature thermometer consisting of a bimetallic sensing element that is shielded from drafts. Other field instruments for determining surface temperature are direct reading thermocouple-type thermometers.

e. With any of the instruments used for determining ambient conditions and surface temperatures, the readings should be taken at the actual location of the work. However, for general readings the coldest and warmest point on the structure should be used to ensure that coatings are not applied outside of their temperature limitations.

f. The date, time of day, location of measurement, and whether or not the work was allowed to commence/continue also should be formally documented.

9-5. Assessing Compressed Air Cleanliness

a. Compressed air used for blast cleaning, blow down, and coating spray atomization must be free from oil and moisture contamination. Contaminants of this type are effectively transferred to the surface with the air and blast-cleaning media (abrasive) or by mixing it with the coating during application. Adequate moisture and oil traps should be used on all lines to ensure that the air is dry and oilfree enough so it does not interfere with the quality of the work. A simple test for determining air cleanliness is outlined in ASTM D4285 and requires holding a clean piece of white blotter paper or a white cloth approximately 457.2 mm (18 in.) from the air supply, downstream of moisture and oil separators. The air is permitted to blow on the blotter paper for a minimum of 1 minute, then the blotter is inspected for signs of detrimental amounts of moisture or oil contamination.

b. A thorough inspection of the surface after blast cleaning for signs of moisture or oil contamination should be made, and these results need to be correlated with the results of the blotter test. In addition, the proper functioning of in-line moisture and oil traps can be evaluated on a comparative basis from the results of the blotter test.

9-6. Measurement of Surface Profile

a. The twofold purpose of surface preparation is to roughen and clean the surface. Specifying a certain blast profile does not indicate the blast cleanliness, which must be addressed separately. The surface profile, anchor pattern, or roughness is defined as the maximum average peak-to-valley depth (or height) caused by the impact of the abrasive onto the substrate. Both SSPC-SP 5 and -SP 6 can have a surface profile of 0.025 to 0.10 mm (1 to 4 mils). Surface profile effectively increases the surface area to which the coatings can adhere, and it provides a mechanical anchor that aids in adhesion. As a general rule, thick coatings require a deeper surface profile than thin coatings.

b. Specifying surface profile is critical. A surface roughness that is too shallow can result in adhesion difficulties, and surface roughness (and insufficient coating thickness) that is too deep can result in pinpoint rusting because unprotected peaks of the profile protrude above the surface of the coating. As a general rule, the surface profile should be a nominal 15 to 20 percent of the total coating system thickness (up to 0.38 mm [15 mils]).

c. Surface profile determinations generally are made in the field or shop with one of three types of instruments: visual surface profile comparators, a depth micrometer, or replica tape. The Civil Works Guide Specification requires the use of replica tape.

(1) Keane-Tator and Clemtex anchor pattern comparators. Visual comparators can be used to assess the average peak-to-valley depth after abrasive blast cleaning. Coupons or discs representing various profile depths are compared with the existing surfaces to determine the surface profile. However, different types of abrasive may result in the appearance of a different profile even though the depths might be identical. For example, a shot-blast profile is round when compared with a more angular grit profile. To achieve similar profile depths, the shot, by virtue of its shape, generally will result in greater lateral distance between peaks than will grit; this will result in a lower peak count per given area. The optical effects provide an illusion that the shot-blast-cleaned surface is deeper than the grit-blast-cleaned surface, even when they are identical. Therefore, it is critical to choose a reference disc or coupon that represents the generic type of abrasive used to clean the surface (i.e., grit/slag, sand, shot) prior to determining the surface profile.

(2) Depth micrometer. Another field instrument useful for determining average profile depth is a depth micrometer. This instrument consists of a conical pin that projects from a large, flat base approximately the size of a nickel. The instrument is calibrated on a mirror or plate glass by turning the entire scale reading so the zero lines up with the pointer. Theoretically, when the instrument is firmly placed on the blast-cleaned substrate, the base will rest on the tops of the peaks and the pin will project into the valley. An average profile can be obtained by taking a number of readings. The instrument must be picked up and placed down for each reading, rather than drag it across the profile. Otherwise, the point will become blunted, resulting in erroneous readings.

(3) Replica tape. Surface profiles can be determined by using replica tape. The replica tape consists of an emulsion film of microscopic bubbles attached to a uniform, 0.05-mm (2-mil) film of mylar. The tape is pressed onto the blast-cleaned surface, emulsion side down, and the mylar is rubbed vigorously with a blunt instrument. The peaks of the profile will break the bubbles and ultimately touch, but not alter, the thickness of the mylar, because it is noncompressible. The tape is removed and measured using a lightweight, spring-loaded micrometer that provides a reading from the upper- or outermost surface of the mylar to the high spots on the emulsion which were not totally

crushed (corresponding with the valleys of the profile). The total micrometer reading is adjusted for the thickness of the mylar to provide a direct reading of the maximum average profile. The tape is available in several grades to measure various profile ranges from less than 1.0 to more than 4.0 mil. The replica tape generally will retain the impression indefinitely if it is stored in a cool area with no pressure applied. Replicas of profiles should be kept on file permanently for future reference. The date, time of day, method used, locations of measurements, and profile measurements should be documented.

9-7. Surface Cleanliness

Surface cleanliness is one of the most critical factors in determining the success of a coating system. Unfortunately, it also is the most subjective of all inspection points. Independent of how well the coating materials are formulated, a surface cleanliness less than that stipulated by the governing specification may result in reduced service life and even premature failure. Volume 2 of the Steel Structures Painting Manual contains the SSPC surface preparation specifications. These specifications describe in narrative form the various degrees of surface cleanliness, the percent of the surface to be cleaned, etc. Similarly, the

National Association of Corrosion Engineers (NACE) has published narrative descriptions of surface cleanliness requirements. Table 9-1 describes the SSPC and NACE cleanliness standards.

a. Assessment of visible contamination.

(1) Assessing surface cleanliness using narrative descriptions can be difficult. As a result, the written standards are supplemented by SSPC VIS 1-89, which photographically depicts the appearance of four grades of blast cleaning (SSPC-SP 7, -SP 6, -SP 10, and -SP 5) over four initial mill scale and rust grades.

(2) NACE also provides visual cleanliness standards. However, NACE encapsulates metal test coupons or plates in a plastic media rather than relying on photographs. Each encapsulated plate contains representative surfaces blast cleaned to the four grades of cleanliness. NACE standards are prepared for sand, steel grit, slag, and steel shot abrasives.

(3) Evaluation of hand- and power-tool cleaned surfaces is accomplished using SSPC VIS 3-93, which photographically depicts the appearance of several grades of

Table 9-1
Surface Cleanliness Specifications

Methods	SSPC Designation	NACE Designation	Definition (as of 1/94)
Solvent cleaning	SSPC-SP 1		Removal of grease, oil, dirt, and other foreign matter by solvents. May entail high pressure water(prerequisite to all other cleanliness specifications).
Hand-tool cleaning	SSPC-SP 2		Removal of all loose materials, tight materials may remain if they cannot be loosened by a dull putty knife.
Power-tool cleaning	SSPC-SP 3		Removal of all loose materials, tight materials may remain if they cannot be loosened by a dull putty knife.
Power-tool cleaning to bare metal	SSPC-SP 11		Removal of all materials from the surface using power tools. A minimum 0.025-mm (1-mil) surface roughness must remain.
Brush-off blast cleaning	SSPC-SP 7	NACE #4	Removal of all loose materials, tight materials may remain if they cannot be loosened by a dull putty knife.
Commercial blast cleaning	SSPC-SP 6	NACE #3	Sixty-six percent of every square inch (surface area) cleaned to white metal; 33 percent of each square inch (surface area) may have stains, streaks, discolorations only. Pitted steel may have traces of rust/paint in pits.
Near-white metal blast cleaning	SSPC-SP 10	NACE #2	Ninety-five percent of every square inch (surface area) cleaned to white metal; 5 percent of each square inch (surface area) may have stains, streaks, discoloration only.
White metal blast cleaning	SSPC-SP 5	NACE #1	One hundred percent of every square inch (surface area) must be clean and have a gray-white appearance.

hand- and power-tool cleaning over seven initial mill scale, rust, and paint grades.

(4) Agreement on the desired appearance of a cleaned surface using commercially available standards may be difficult to achieve because of shadows and hues caused by the abrasive, the pattern and degree of prior rusting, and numerous other factors unique to each project. As a result, jobsite standards frequently are developed. Sections of the structure (or test panels of a similar nature) are prepared, and all parties involved ultimately select one of the panels or areas that represents the desired end result.

(5) Cleanliness after surface preparation also is important. Residual traces of abrasive must be blown, swept, or vacuumed from the surface prior to prime coating. Dust must be removed from the surface prior to painting, particularly the fine film of dustlike spent abrasive often held to the blast-cleaned surface by static electricity. Many painters who are using conventional spray equipment use the spray gun to blow down the surface prior to the paint application; this cannot be done in the same manner if airless spray equipment is used. Any scaffolding, staging, or support steel above the area to be coated must be blown down and cleaned to prevent abrasive dropping onto the freshly cleaned surface, or later contaminating the freshly primed surface. Concurrent blast cleaning and painting should not be permitted, unless the blast cleaning is adequately isolated to prevent contamination of the freshly painted surface.

(6) Inaccessible areas (back-to-back angles, areas between rivets and support members, etc.) can be difficult to properly clean for application, compared to the relatively accessible, large, flat areas. Careful inspection of these inaccessible areas is required and can be evaluated using small inspection mirrors. The worker may have to use special blast nozzles (abrasive exits from the side, not end) or other tools to sufficiently clean the inaccessible areas. During evaluation of surface cleanliness, the inspector should wear gloves to prevent contamination of the steel. Although it is impractical to inspect every square inch of a structure, the inaccessible areas discussed here must be thoroughly inspected and the accessible areas should be spot-checked for contract compliance.

(7) The date, time of day, location, and cleanliness achieved should be documented as well as the standard used to evaluate the degree of cleanliness.

b. Assessment of invisible (chemical) contamination.

(1) Coating over even small amounts of soluble salt contamination can result in premature coating failure. Salt

is hygroscopic and, when trapped beneath a coating film, will osmotically pull moisture from the atmosphere through the semipermeable membrane (coating.) This commonly results in underfilm corrosion and/or osmotic blistering.

(2) Evaluation of the surface for invisible contamination can be accomplished in a number of ways. Perhaps the most common field method is a technique in which a premeasured area of the surface is swabbed with a known amount of deionized water, using a cotton ball, and handling with tweezers or plastic gloves. The test water is analyzed using silver-nitrate-treated test strips, which precipitate a white coloration when placed in contact with sodium chloride. The resulting parts per million are converted to micrograms of chloride by multiplying the parts per million by the amount of water used in the swabbing. Micrograms of chloride are divided by the area sampled to achieve micrograms per square centimeter of chloride.

(3) The amount of chloride that can be tolerated depends on the coating type and the service environment. However, as a general rule, the threshold for an acceptable surface lies at or below 5 micrograms per square centimeter ($\mu\text{g}/\text{cm}^2$) of chloride.

(4) Effective methods of removing chemical contamination include high-pressure water washing and steam cleaning prior to other methods.

c. Removal of burrs, slivers, hackles, etc. Abrasive blast-cleaning procedures may result in the development of burrs, slivers, hackles, and other surface irregularities, particularly if a large, angular abrasive is used. Burrs, slivers, and hackles may protrude above the coating film and expose unprotected steel to the atmosphere, resulting in pinpoint corrosion. Grinding is typically required for removal of these surface defects. However, the surface must be reblasted to restore the original profile after grinding.

9-8. Paint Storage, Mixing, and Thinning

Material receipt inspection and inspection of mixing and thinning procedures are two of the most simple, yet crucial, steps in the coatings process. Each step requires some knowledge of the procedure.

a. Material receipt inspection. On receipt of all coating materials, the inspector should document the number of components received for each material; confirm the manufacturer, product, and color; and record the batch number from the can label. The inspector should compare the batch numbers with those on the test reports to ensure that the proper batches were received. Leaking or damaged

containers should not be used, particularly if a catalyzed paint is involved because some of the components necessary for a complete cure may have leaked out, and proper proportioning may not be obtainable. Containers with illegible labels should not be used. The inspector should confirm that the shelf life of the material has not expired and that the manufacturer's product data sheets and material safety data sheets (MSDS) were received with the shipment. Paint more than 1 year from date of manufacture should be retested. Paint storage areas should be maintained with proper ventilation and temperature controls to prevent excessive heat or freezing conditions. Paint stock should be rotated to facilitate the use of older materials first, if the shelf life is still current.

b. Inspection of mixing and thinning procedures.

(1) Improper mixing or thinning will affect the coating's ability to resist the service environment. There should be some means to ensure that all components of the multicomponent paint system have been added, that mixing is thorough and proper, and that any required induction times have been met. An induction time (cook time; sweat-in-time) is required by some coating types to allow a chemical reaction to initiate, prior to application. Induction times are temperature dependent; typically the warmer the temperature, the shorter the required induction because heat increases the rate of reaction.

(2) Mixing should be done until the paint becomes smooth, homogeneous, and free of surface swirls or pigment lumps (agglomerations). Many paints settle out on prolonged storage. Boxing (repetitive emptying of the contents of one container into a second empty container) of these paints is beneficial to ensure that all pigment settled on the bottom of the container is incorporated in the mixed paint. Paint mixer blades mounted in a pneumatically operated power tool provide sufficient agitation.

(3) All paints should be strained prior to spraying to eliminate skins, improperly mixed pigments, or agglomerations of zinc particles. This usually is accomplished by passing the mixed paint through a disposable cheesecloth bag filter prior to putting the paint into the spray pot. Coarse filters are common on the intake line of conventional spray equipment, and fine filters typically are built in to airless systems. When adding zinc to a multicomponent coating, it is common to sift the dry powder through a screen into the liquid portion while mixing.

(4) Coatings that contain heavy pigments, such as zinc dust, frequently require constant agitation throughout the application process. The agitator should be run as rapidly

as necessary to maintain pigment suspension, but not rapidly enough to entrain air into the paint. After spraying has started, a flow of the material through the lines should be maintained to prevent the heavy pigment from settling out. Some coating manufacturers recommend hoses be whipped or emptied if spraying is interrupted for specified lengths of time.

(5) Preferably, only complete kits of multicomponent paints should be mixed. If this cannot be done, the coating manufacturer should be consulted to assure that partial mixing of the materials is permitted, and it is imperative that the components be carefully measured.

(6) The temperature of the mixed coating material should be measured and documented. Typically a metal "dip stick" paint thermometer is used.

(7) Thinners, if permitted, should be well mixed into the paint material. The type and amount of thinner should be in accordance with the coating manufacturer's recommendations. The amount of thinner used should be recorded by the inspector because the addition of thinner reduces the volume of the solid content of the mixed paint and may violate VOC regulations.

(8) Measurement of viscosity assures that proper thinning ratios are used, and that the thinning has not been changed significantly from pot to pot. There are many ways to measure the viscosity of a paint. Common viscosity cups are simply small cups of known volume with precisely sized orifices in the center. Viscosity cups place a numerical value (time) on the viscosity of a paint material. The coating manufacturer can be consulted about what orifice size to use and the time in seconds for the volume of properly thinned material held by the cup to pass through the orifice. For example, the manufacturer might stipulate that the material should be thinned so it will pass through a specific viscosity cup in 20 to 30 seconds. Temperature greatly influences viscosity, and the temperature of the material should be noted when conducting viscosity measurements.

(9) High viscosity materials may not atomize properly if they are not adjusted with thinner, and low viscosity materials may run or sag on application if they are not properly reduced. The paint applicator is generally the best judge of proper thinning ratios to achieve a smooth, wet coat without runs or sags. The viscosity of some high buildup coatings cannot be measured with viscosity cups, and the manufacturer should be contacted for a recommendation. Alternatively, coatings can be thinned by volume with a percentage of the recommended thinner, based on a known volume of coating material.

(10) The potlife of a coating material also must be monitored by the inspector. Potlife is unique to multicomponent coatings; it is the time period within which the mixed coatings material may be used. The potlife varies from coating to coating and is temperature dependent. The warmer the temperature, the shorter the potlife. The inspector also must keep in mind that an induction time uses a portion of the potlife. The remaining material must be discarded when the potlife is expired. The end of the potlife usually can be detected by the increased viscosity of the coating. This is not always true; therefore, the potlife should be monitored based on time and temperature. To counteract the increase in viscosity as the potlife nears the end, contractors may add thinner to the mixed coating. The coating manufacturer should be consulted to ensure that this practice does not adversely affect the paint material.

9-9. Coating Application Technique

Aside from surface preparation, the actual coating application is the most visible and important aspect of the coating work. Accordingly, the inspector should be knowledgeable about the various application techniques. These will be reviewed here briefly and are discussed in more detail in Chapter 8.

a. When spraying with conventional (air atomized) equipment, the spray gun should be held 203.2 to 254 mm (8 to 10 in.) from the surface and maintained perpendicular to the surface throughout the stroke. The distance should be 304.8 to 457.2 mm (12 to 18 in.) for airless spray application. Holding the spray gun further from the surface may result in overspray and dryspray; holding the spray gun too close may cause excessive application (runs, sags, and entrapped air and solvents.) In addition to spray gun distance, the spray pressures should be maintained as low as possible to prevent overspray and flooding of the surface, yet high enough to support atomization. At the end of each pass, the spray gun trigger should be released so the passes feather into one another. Each spray pass should overlap the previous one by 50 percent to create uniformity and, when possible, a cross-hatch technique should be used. This requires a duplicate series of passes 90 degrees to the first to ensure complete and uniform coverage. Proper cleaning of equipment is important to ensure that there is no contamination of a new coating by residues of the previous coat passing through the equipment or by incompatible cleaning solvents. Proper cleaning of the equipment is particularly important when using zinc-rich vinyls, since the vinyl topcoats are incompatible with the zinc pigment.

b. For brush application, the brush should be dipped approximately one half of its bristle length into the coating. The bristle tips should be brushed lightly against the side of

the container to prevent dripping, and as fully a loaded a brush as possible should be maintained. This will result in a more even coating film and help ensure thorough wetting of the surface. Brushing is more effective than spraying for working paint into depressed irregularities, pits, or crevices. Care should be taken to ensure that the coating is not brushed out too thin, especially on projections and corners.

c. In general, the inspector should ensure that, independent of the application method, the equipment used is providing a quality coating film. The inspector also should reference the coating manufacturer's product data to ensure that the application equipment complies with the recommendations of the manufacturer. For example, brush or roller application of an inorganic, zinc-rich primer generally would not be an acceptable practice because coating thickness using these methods is too difficult to control, and the coating itself is too heavily pigmented to apply using brush/roller techniques.

9-10. Measurement of Wet Coating Thickness

The wet thickness of an applied coating film should be measured to ensure that sufficient dry coating will be present after solvent evaporation and curing. Guessing or approximating the amount of wet coating to apply will almost certainly result in insufficient or excessive coating thickness. A wet film thickness gage can be used to monitor the amount of wet coating applied. However, without incorporating the specified dry coating thickness and percentage of solids by volume of the coating into a calculation, wet film thickness data are meaningless. This calculation is explored in the following discussion.

a. A coating is formulated using three basic components: a resin or binder, pigment, and solvent. The resin (binder) and pigment comprise the solids portion of the coating. The solvents comprise the volatile portion of the paint. When calculating wet film thickness, the solids by volume (pigment/resin content by volume) is an important figure and is typically derived from the manufacturer's product data sheets. The basic formula for calculating wet coating thickness is found in Equation 9-1.

$$\text{Wet film thickness} = \frac{\text{dry film thickness}}{\% \text{ solids by volume}} \quad (9-1)$$

Equation 9-1 is accurate if the solids by volume of the material is accurate. However, the percentage will change if any thinner is added to the coating. When thinner is added, the total volume of the material is increased without any corresponding increase in the amount of solids. Therefore, the thinned material will result in a lower

percentage of solids by volume. Thus, when comparing thinned versus unthinned material, to achieve a comparable dry film thickness, a heavier wet film application of the thinned material is required.

b. Because the use of a wet film thickness gage depends on the solids by volume, and the solids by volume is considered the "in can" percentage, wet film thickness readings must be taken as soon as a film is applied to the surface. During spray application, between the time the material leaves the spray gun and reaches the surface, some of the solvents will already have evaporated, changing the percent of solids by volume slightly. For most applications, this change is not too significant; however, the rapid evaporation rate of the solvents used in lacquer materials, such as vinyl and chlorinated rubber paints, makes wet film thickness measurements of these coatings meaningless. The longer the amount of time before a measurement is taken, the less accurate the measurement becomes. For highly pigmented coatings (such as zinc-rich), wet film thickness readings may be unreliable because, even though the coating contains a percentage of solvent, the shrinkage from solvent loss may be low. Obviously, on 100 percent solids coatings, the wet film thickness will equal the dry film thickness.

c. The wet film thickness gage is generally of a standard notch configuration. The notch-type gage consists of two end points on the same plane, with progressively deeper notched steps in between. Each step is designated by a number representing the distance in mils or microns between the step and the plane created by the two end points. The instrument is pressed firmly into the wet film perpendicular to the substrate then withdrawn. The two end points will be wetted by the coating material, as well as some of the steps in between. The wet film thickness is considered as the last wetted step before the next adjacent, higher dry one.

9-11. Nondestructive Measurement of Dry Coating Thickness

a. Dry coating thickness readings on steel substrates are commonly taken using magnetic gages. Nonmagnetically operated equipment is used for nonferrous metallic substrates. Calibration of all coating thickness gages and measurement of coating thickness should be performed in accordance with ASTM D1186 or ASTM D1400.

b. Determination of the thickness of each coat in a multicoat system should be an inspection point, especially when each coat is generically different. For example, if an inorganic zinc primer/epoxy intermediate/urethane topcoat system is specified, each layer should be measured to ensure proper thickness because coating thickness gages will not

yield individual layer thickness after subsequent coats are applied. When using nondestructive gages to measure multicoat systems, the average thickness of the first coat must be determined prior to application of the second coat. Readings taken after the second coat is applied obviously will be the total thickness of the two coats combined, and the specific thickness of the second coat can only be determined by subtracting the average thickness obtained from the first coat reading.

c. It is a good idea, where practical, to provide a means to indicate coating thickness in areas where it is either thin or thick so appropriate repair can be done by the coating applicator. Possible methods are brush application of a light tinted coat of the same paint, compatible felt tip marking pens, chalk, or other material that can be readily removed. Wax crayons or incompatible spray paints should not be used.

d. Thickness readings are taken to provide reasonable assurance that the specified thickness has been achieved. However, it is not possible to measure every square inch of the surface. Both ASTM D1186 and D1400 state that, when using coating thickness gages, five separate spot measurements should be made over every 9.3-sq-m (100-sq-ft) area. Each spot measurement consists of an average of three gage readings taken within a 12.7-mm- (1/2-in.-) diameter circle.

e. Nondestructive dry film thickness measurement instruments fall into three basic categories: magnetic pull-off, electromagnetic probe, and eddy current probe. Destructive dry film thickness gages are addressed separately.

(1) Magnetic pull-off gages.

(a) Magnetic pull-off gages commonly consist of a lever running through the center of a scale dial that houses a helical spring. The scale dial is located at the fulcrum point of the lever. One end of the spring is attached to the lever and the other end to the scale dial. One side of the lever contains a permanent magnet and the opposite end contains a counterbalance.

(b) The spring tension overcomes the attraction of the magnet to the substrate and lifts the magnet from the coating surface. The spring tension is calibrated so the point where the magnet breaks contact with the surface can be equated to the distance of the magnet from the surface. This distance is converted to mils (or microns.) The thickness reading represents the gap between the magnet and the substrate. This gap is considered to be the coating thickness. However, this reading could be compromised by

voids, rust, embedded contaminants, mill scale, etc. Therefore, a thorough visual inspection needs to be included during the work to ensure that the coating is applied over a clean surface and does not become contaminated during drying.

(c) Magnetic pull-off coating thickness gages should be calibrated, or at least calibration verified, prior to, during, and after each use to assure that they are measuring accurately. Calibration is described in ASTM D1186. Plastic shims of known thicknesses are placed directly onto the blast-cleaned surface, and the gage is adjusted to closely match the shim thickness. One or two shims that represent the actual field coating thickness should be chosen so calibration can be performed in the range of use. The user must bear in mind that the accuracy of magnetic pull-off gages ranges from 5 to 10 percent of the reading, and that minor deviations from the specified thickness is not cause for rejection.

(2) Electromagnetic probe.

(a) Electromagnetic probe gages for ferrous surfaces are described in ASTM D1186. These gages also are calibrated prior to use with the nonmagnetic (plastic) shim method. Most of the coating thickness gages used in the corrosion control industry are of this type. They are accurate (± 3 to 5 percent of reading, depending on manufacturer), provide a digital display of the thickness, and eliminate user interpretation of an analog scale. Also, this type of gage commonly is equipped with a microprocessor capable of storing measurements in memory and performing statistical evaluations of the stored data including mean, standard deviation, highest and lowest readings, and total number of readings obtained. These data frequently can be downloaded to a computer and/or printer, and can save considerable amounts of time related to hand documentation of measurements, as well as averaging and determining thickness ranges. However, because these gages are electronic, they are more delicate and more susceptible to field damage compared to the mechanical pull-off gages. Also, these gages are more sensitive to rough surfaces than mechanical types.

(b) Eddy current probe gages, described in ASTM D1400, measure the thickness of nonconductive coatings applied to nonferrous metal substrates. The probe is energized by alternating magnetic fields within the metal and modifying the electrical characteristics of the probe coil. The extent of these changes is determined by the distance of the probe from the substrate and is shown on the gage meter as coating thickness. The eddy current probe gages are calibrated in a manner similar to that for the electromagnetic probe gages using the plastic shims on a nonferrous metal

substrate. Some gages combine both electromagnetic probe and eddy current probe capability in one unit.

(3) Precautions. Some precautions are necessary when using any instrument with a magnet. The magnet is exposed; therefore, it is susceptible to attracting iron filings, steel shot, or grit particles. The magnet must be cleaned of any contaminants during use, or the contaminants will cause incorrect readings. If the instrument is used on a soft coating film, a plastic shim can be placed on top of the surface to prevent the magnet from deforming the coating. The shim thickness is subtracted from any subsequent readings. Vibrations in the area of instrument use can cause the magnet in pull-off gages to be released from the surface prematurely, which can result in an erroneously high thickness reading. Dry coating thickness instruments should not be used any closer than 1 in. to an edge of the surface; residual magnetism in the structure on which the coating is measured can have an erroneous effect on the readings. The scale dial-type instruments (magnetic pull-off) have an additional "human error" problem during use because it is easy to continue to turn the dial beyond the point the magnet has lifted from the surface, which would result in an incorrect thickness measurement. Therefore, it is imperative that the dial be stopped as soon as the magnet releases from the surface.

f. The inspector should document the date and location of measurements, the type of coat being measured (primer, intermediate, topcoat), the product and the type of gage being used, the calibration method, and whether or not the area inspected meets the specification.

9-12. Destructive Measurement of Dry Coating Thickness

Destructive thickness testing entails the use of the Tooke¹ gage (or paint inspection gage). The Tooke gage measures the thickness of nearly any coating applied to ferrous and nonferrous metals and other nonferrous surfaces, including masonry, plastic, wood, etc. The gage consists of a 50X microscope that is used to look at slits in the coating made by precision cutting tips supplied with the instrument. The principle of the Tooke gage is basic trigonometry. By making a cut through the coating at a known angle and viewing perpendicularly to the cut, the actual coating thickness can be determined by measuring the width of the cut from a scale in the eyepiece of the microscope. The instrument can be used for determining the thickness of underlying coats in multicoat systems (if the layers are alternating or different colors) and eliminates many of the

¹ Tooke Gage; Micro-Metrics; Atlanta, Georgia.

drawbacks of the magnetic instruments that are caused by magnetic fields, proximity to edges, irregular surfaces, magnetic effect of the substrate and profile, etc. The instrument can be used on coating thicknesses up to 1.27 mm (50 mils) if the coating is not too brittle or elastic for a smooth cut to be made. The Tooke gage has limitations. The use of the gage can be tedious and slow, and it creates voids (cuts) in the coating system that must be repaired. The gage becomes impractical on large field structures where paint thickness often lacks uniformity. However, the Tooke gage is often used as a final determination of thickness at specific, selected locations.

9-13. Cleanliness and Time (Cure) Between Coats

When more than one coat is to be applied, a determination of the cleanliness of the surface immediately prior to application of the next coat is required. In addition to dirt and dust, dry spray or overspray may cause a problem. All dirt, dust, and other contaminants should be removed because their presence can result in reduced adhesion between coats and porosity in the subsequent coat, which could render the coating less resistant to environmental effects. The surface also should be inspected for any adverse contamination from the environment. In addition to intercoat cleanliness, the recoat window also must be observed. Recoating too soon may cause solvent entrapment, wrinkling, and other film defects; exceeding the recoat window may result in intercoat adhesion difficulties (common with CTE and moisture cure urethane systems). Evaluation of cure is discussed in paragraph 9-16.

9-14. Holiday/Pinhole Detection

a. A holiday is a skip or miss on the coating film, while a pinhole is typically a microscopic hole in the coating film. Holiday, pinhole, or spark testing can be used to find the nicks, scrapes, and pinholes in the coating film. Pinholes can be present in any coating layer and should be closed before the next coat is applied. Pinhole testing is common when the coating is intended for immersion service. Holiday testing may be required after application of either the next to the last, or last, coat of paint. Usually when such testing is specified, the test is done when the coating is sufficiently dry but before final cure has occurred so that repair material will successfully bond to the underlying coats.

b. Pinhole and holiday detectors are of two general types: low-voltage wet sponge and high-voltage.

(1) Low-voltage wet sponge pinhole detectors. The low-voltage wet sponge pinhole detectors are used for finding discontinuities in nonconductive coatings applied to

conductive metal surfaces. Pinhole testing also can be used to locate conductivity on rivets, bolt threads, etc. This testing should be followed by a visual examination for the deficient area(s.) The low-voltage detector is suitable for use on coatings up to 0.51 mm (20 mils) in thickness. The basic unit consists of the detector itself, a ground cable, and a sponge electrode. The ground cable is firmly attached to the bare substrate, and the sponge electrode is saturated with tap water. When the electrode is moved across the entire surface, the water permits a small current to flow through the pinholes down to the substrate. When the current reaches the substrate, the circuit is completed to the detector unit and an audible signal indicates that a pinhole or discontinuity is present. When coatings are above 0.254 mm (10 mils), a nonsudsing, wetting agent (such as a photographic developing fluid) may be added to the water to increase the wetting properties. Compatibility of the wetting agent with the coating to be applied must be verified. If the coating system is found to be outside the 0.51-mm (20-mil) thickness limits, high-voltage holiday detection equipment should be used. Pinhole testing has certain limitations. For example, in some situations, pinholes can be visually detected, though the detector does not sound, because the pinholes do not penetrate to the substrate. Conversely, the detector may sound to indicate the presence of a void when none exists because the coating itself may be conductive as a result of metallic pigmentation or entrained solvent.

(2) High-voltage holiday detectors. High-voltage detectors basically function on the same operating principle as the low-voltage units, except a sponge is not used. The instrument consists of a testing unit capable of producing various voltage outputs, a ground cable, and an electrode made of neoprene, rubber, brass, or steel. High-voltage units are available up to 20,000 V and more. High-voltage holiday inspection frequently is required on pipelines and other critical applications. A spark will jump from the electrode through the coating down to the substrate at pinholes, holidays, or missed areas and simultaneously trigger an audible and/or visual signaling device in the unit. The rule of thumb for high-voltage testing is 100 to 125 V per mil. For example, a 1.02-mm (40-mil) coat will require a test voltage of 4,000 to 5,000 V. Too high a test voltage may damage the coating film. Even when the test voltage is properly set, a spark may penetrate a thin, intact area of the coating and create a void that must be repaired.

9-15. Adhesion Testing

a. Occasionally, there is a need to test the adhesion characteristics of the coating film after application and cure. Adhesion testing is commonly conducted using either of two field methods: tensile adhesion and knife (tape) adhesion.

Tensile adhesion is performed in accordance with ASTM D4541-89. Tensile adhesion requires that a pull stub be adhered to the coating surface using an epoxy adhesive. The pulling force (measured in pounds per square inch) required to disbond the pull stub is a measure of the coating system's tensile adhesion. Additionally, the break in the coating system is described as adhesion (a break between layers or between the substrate and first layer), cohesion (a break within a coating layer), or glue (failure of the pull stub to adequately bond to the surface of the coating). Knife (tape) adhesion requires making an X-cut or a series of parallel and perpendicular knife cuts through the coating (cross-hatch grid), pulling tape from the X or grid, and evaluating the percentage of disbanded coating. The grid or cross-hatch method is used for coatings 0.127 mm (5 mils) or less. The X-cut is used for coating systems in excess of 0.127 mm (5 mils).

b. Adhesion test data will not predict the performance life of a coating system. A coating system with good-to-excellent adhesion probably will protect the substrate longer, but a coating system with marginal adhesion may protect just as long if the coating remains intact. Adhesion testing can be used as one tool to determine whether or not an existing coating system is a candidate for overcoating. Adhesion testing should be performed prior to applying test patches of candidate overcoat systems, and it can be used to evaluate the performance of the overcoating candidates after it is applied and cured.

9-16. Evaluating Cure

a. When a coating is designed for immersion service, the applied coating film must be allowed to cure prior to being placed into service. This curing time generally is

shown on the manufacturer's product information. Alternately, forced-heat curing may be used to reduce the time between curing and service.

b. Determining the cure of coatings generally is difficult. ASTM D1640 is one method, but there are no universally reliable field tests for such purposes. Because a coating is dry or hard does not necessarily mean it is cured. In fact, hardness is not synonymous with cure for most coatings. The only types for which this is true are the solvent-deposited coatings such as the chlorinated rubbers and vinyls. Residual retained solvents (and moisture in water-emulsion coatings), under certain atmospheric conditions of temperature and/or humidity, may require a longer period of time to escape from the paint film. Final attainment of film properties will be acquired only on satisfactory loss of these entrapped solvents. In some situations this evaporation process may take as long as 2 to 3 weeks or more.

c. Solvent rub tests and sandpaper tests can be used to approximate the degree of cure. When most coatings are suitably cured, rubbing them with sandpaper will produce a fine dust. If the sandpaper gums up, depending on the coating, it may not be cured properly. A solvent rub test is frequently performed to check the cure of inorganic zincs. For this test, a cloth saturated with MEK is rubbed onto the coating a specific number of times.

d. Epoxies, urethanes, and other generic coatings (catalyzed and noncatalyzed) can be evaluated for cure according to ASTM D1640, which describes procedures for conducting set-to-touch, dust-free, tack-free, dry-to-touch, dry hard, dry through, dry-to-recoat, and print-free dry/curing times.

Chapter 10 Safety

10-1. Introduction

Coating and surface preparation operations inherently expose workers to many potential safety and health hazards. Because of the high frequency rate of accidents in the coating industry, painting is considered a high hazard occupation. Some common safety and health hazards associated with painting include: improper selection and/or use of personal protective equipment such as respirators for toxic chemical control; operating abrasive blast-cleaning equipment at high pressure; storage and use of flammable liquids; work in confined spaces; toxic effects from exposure to chemicals in coating materials; ignition sources such as welding, burning, and cutting that may cause solvents to ignite or produce toxic airborne contaminants.

10-2. Hazardous Material Handling

a. Coating materials. The primary components in industrial coating materials are commonly grouped into four general categories: binders, pigments, organic solvents, and additives. The chemicals that make up these components affect the nature and type of hazards presented during use. Most coating materials present both a health hazard and a flammability hazard. A coating material may be considered a health hazard when its properties are such that it can directly or indirectly cause injury or illness, either temporary or permanent, from exposure by direct skin contact, inhalation of vapors as the liquid portion evaporates, or inadvertent ingestion. The components of coating materials have varying health effects, depending on the toxicity of the particular component. Some chemicals may cause irritation, sensitization, central nervous system effects, or systemic effects. Chemical exposure for short periods of time at low doses can be tolerated; however, immediate sensitivity to some ingredients may occur. Extended exposure almost always will cause some type of reaction. Continued exposure may cause the body to become sensitized so subsequent contact may result in an aggravated reaction, especially for anyone with a chronic illness. A discussion of some health hazards related to coating material components follows.

(1) Binders. All resins or binders are toxic to some degree if exposure is excessive. The primary health hazard associated with binders generally is related to skin contact. Some binders may be strong sensitizers and cause an allergic reaction. Specifically, epoxy resins used in USACE formulations E303 zinc rich epoxy and C200 coal tar epoxy and military formulation MIL-P-24441A polyamide epoxy

may cause allergic reactions with certain workers, depending on their sensitivity to these epoxy resins. The use of chemically resistant gloves, aprons, safety goggles, and face shields must be enforced to help avoid contact with the epoxy resins. Special attention also must be given to urethane coating systems such as those specified in MIL-C-83286B. The two-component urethane coating systems are formed by the reaction of the diisocyanate and a polyester. Diisocyanate compounds are irritants to the eyes, nose, and throat on initial exposure. Some workers exposed to low doses (low airborne concentrations) may develop respiratory tract sensitization. Once sensitized to diisocyanates, the health effect is similar to asthma-like symptoms. To control exposure, workers must wear protective clothing as described while handling epoxy resins. Protective clothing and a supplied-air respirator must also be worn while handling polyurethanes.

(2) Pigments. The use of common heavy metal compounds—including lead, cadmium, and chromium—historically have presented health hazards. These metals are all toxic to many internal body systems. The recent introduction of less toxic pigments such as iron, titanium, and zinc have helped to reduce this potential hazard. The heavy metal pigments present the greatest health hazard during coating-removal operations. This is especially true with lead.

(3) Organic solvents. A wide variety of organic chemicals, typically referred to as solvents and thinners, are used in the formulation of coating materials. Control measures to prevent the health effects of solvent exposures include providing adequate ventilation to dilute vapors to safe levels, referencing the MSDS to select the proper protective clothing, avoiding unnecessary or prolonged skin contact, and using appropriate respiratory protection if the concentration of vapor in the air is above permissible levels. The health hazards associated with solvents depend on many variables, including the toxic characteristics unique to that solvent, level of exposure (the dose), the duration of exposure, and the route of entry into the body. The principal routes of entry into the body for solvent exposure are inhalation of the vapors and skin contact. The most common result of skin contact with a solvent is irritation. It should be recognized that, although most solvents will cause skin irritation at the site of contact, some solvents also may be taken into the body through skin absorption. Some common solvents that can be absorbed through the skin include several alcohols, toluene, and some specific ketones. The MSDS for the solvent should be reviewed to determine skin absorption capabilities. The following summary is provided to illustrate the various health effects of solvents commonly found in industrial coating materials. Many solvents have overlapping symptoms that make determining

which solvent is causing a problem difficult if more than one type of solvent is used. Solvents also can have a synergistic effect, which means that, if two solvents are used that are both harmful in the same way, the symptom will be more than double.

(a) Skin irritants. Most organic solvents remove the natural oil from the skin. Removal of the oil causes reddening, chapping, drying, and cracking of the skin at the point where the solvent contacts the skin. Contact usually occurs on the hands and forearms. The effect usually is not serious, and affected areas heal when exposure ceases.

(b) Mild respiratory irritation. The vapors of some solvents will cause eye, nose, and throat irritation because they are highly soluble with the moist mucous membranes of the upper respiratory system. These effects usually are not serious, and they disappear as soon as the person is removed from the toxic environment and given fresh air. However, the concern is that the toxic substance has entered the body and may cause systemic problems.

(c) Nervous system effects (solvent neurotoxicity). Most solvent vapors can act on either the central nervous system or the peripheral nervous system (hands, legs, arms, and feet). These vapors can produce headaches, drowsiness, convulsions, behavior changes, tremors/shaking, and loss of feeling and control. Most of these effects are short term; however, some specific solvents produce permanent disabilities.

(d) Nephrotoxins (kidney) effects. Chronic exposure to nephrotoxins can cause damage to the kidneys. These effects must be considered serious; they are permanent and, in extreme cases, may be fatal.

(4) Additives. Most additives make up only a small percent of the coating material and usually do not present much of a health hazard. The MSDS should be reviewed to assess the types of additives in the coating material and the nature of the health hazards that may result.

b. Flammable/combustible liquids. The presence of organic solvents in industrial coating materials and thinners presents significant fire and explosion hazards. Virtually all solvent-based coatings and thinners are highly flammable in liquid form, and vapors released in the process of application are explosive in nature if concentrated in sufficient volume in closed or restricted areas.

(1) Classification of flammable and combustible liquids.

(a) According to the National Fire Protection Association (NFPA), a flammable liquid is a liquid with a flash point

below 37.8 °C (100 °F). A flash point is the lowest temperature at which a liquid gives off enough vapor to form an ignitable mixture with air and to flash (produce a flame) when a source of ignition is present. Highly flammable liquids have extremely low flash points. At the typical ambient temperatures most coatings are applied, solvents such as alcohols, acetone, toluene, or methyl ethyl ketone can give off enough vapors to ignite easily.

(b) A combustible liquid is one with a flash point above 37.8 °C (100 °F). Common solvents include mineral spirits, high flash naphtha, and methyl isoamyl ketone. To determine the flash point of a coating material, refer to the MSDS.

(2) Lower explosive limit/upper explosive limit.

(a) Liquids do not burn or explode, but their vapors do. For this reason, understanding the concept of lower explosive limit (LEL) and upper explosive limit (UEL) is important for the prevention of explosions. The explosive or flammable range of a solvent is the percentage range of the solvent vapor in air, by volume, within which the vapor concentration is sufficient to support combustion. The range is defined by the minimum concentration (LEL) and the maximum concentration (UEL) of vapor in air necessary to allow the vapor to ignite. A mixture of air and flammable vapor will burn or explode only within these concentrations or limits. For example, toluene has an LEL of 1.2 percent and a UEL of 7.1 percent. This means the airborne concentration must fall in this range for the toluene vapor-air mixture to ignite or explode. Airborne concentrations of toluene less than 1.2 percent are too "lean" to support combustion. From a safety viewpoint, knowledge of the LEL is important because most operations start with concentrations of a flammable vapor well below this limit and build up to the explosive range.

(b) The airborne concentration of a solvent required to have an explosive atmosphere is much higher than that required to have a toxic atmosphere. For example, OSHA has established a permissible exposure limit (PEL) of 200 parts per million (ppm) for toluene. When workers are exposed to levels of 200 ppm or above, irritation and central nervous system effects may occur. As discussed in the previous paragraph, a concentration of 12,000 ppm (1.2 percent) is required to reach an explosive atmosphere of toluene.

(c) The LEL for solvents varies and depends on the specific chemical or mixture of solvent. Determining just how quickly an LEL can be achieved is difficult because it depends on the type and volume of vapor in a given space. LEL can be measured using a combustible gas indicator

that measures total hydrocarbons in the atmosphere. OSHA Standard 29 CFR 1910.146, currently establishes a guideline that no space should be entered if the concentration of flammable vapors in air equals or exceeds 10 percent of the LEL.

(3) Determining ventilation needed to control explosion hazards.

(a) A danger when coating in enclosed spaces is that the solvent vapor buildup in the entire space, or a sizable portion thereof, will be enough to reach the LEL. However, coating in enclosed spaces can be made entirely safe if adequate ventilation is provided.

(b) The volume of air per hour required for the dilution of vapors to the LEL is calculated using Equation 10-1.

$$\begin{aligned} &\text{Volume of air (cubic feet per hour)} \\ &= \frac{\text{vapor volume per gallon liquid} \times 100}{\text{lower explosive limit (\%)}} \quad (10-1) \end{aligned}$$

The vapor volume is the number of cubic feet of solvent vapor formed by the evaporation of 3.78 L (1 gal) of solvent. Equation 10-2 shows how to calculate vapor volume.

$$\begin{aligned} &\text{Vapor volume (cubic feet per gallon)} \\ &= \frac{\text{specific gravity of solvent} \times 8.31 \times 392}{\text{molecular weight of the solvent}} \quad (10-2) \end{aligned}$$

Using toluene as an example, Equations 10-3 and 10-4 demonstrate how to calculate the total volume of air needed to prevent a flammable concentration if 3.78 L (1 gal) of toluene is evaporated per hour.

$$\begin{aligned} \text{toluene: } &\text{specific gravity} = 0.9 \\ &\text{molecular weight} = 92 \\ &\text{LEL} = 1.2 \text{ percent} \\ &= \frac{0.9 \times 8.31 \times 392}{92} = 31.86 \quad (10-3) \end{aligned}$$

$$\begin{aligned} &\text{Volume of air per hour for dilution to LEL} \\ &= \frac{31.86 \text{ cubic feet} \times 100}{1.2\%} \\ &= 2,655 \text{ cubic feet per hour} \\ &= 44.25 \text{ cubic feet per minute} \quad (10-4) \end{aligned}$$

Therefore, the minimum volume of air needed to ensure dilution of toluene vapors to the LEL is 1.24 m³ per minute (44.25 cubic feet per minute [cfm]). Generally, a safety factor of 10 is applied when controlling flammable vapor mixtures. Thus, by using a safety factor of 10, at least 120 (10 × 44) m³ per minute (440 [10 × 44] cfm) should be exhausted and replaced with outside air for each gallon of toluene evaporated per hour in a space. Air in a confined space must be moving to prevent pockets of higher concentration.

(c) The next step is to determine the amount of solvent used per hour. For instance, the foregoing example would apply to one applicator rolling on 7.56 L (2 gal) of coating containing 50 percent by volume toluene in a 1-hour period. So 3.78 L (1 gal) of toluene, or 0.89 m³ (31.86 cubic feet) of vapor, theoretically would evaporate in a 1-hour period. Spray guns will apply up to 1 quart of liquid per minute or 56.7 L (15 gal) per hour. Assuming a 50 percent concentration of toluene, 28.35 L (7.5 gal) of toluene could be evaporated per hour. In this situation the calculation for determining the amount of air needed for proper dilution is given in Equation 10-5.

$$\begin{aligned} &= \frac{7.5 \text{ gal} \times 31.86 \text{ cubic feet} \times 100}{1.2\%} \\ &= 19,912.5 \text{ cubic feet per hour} \\ &= 332 \text{ cfm} \\ &= 3,320 \text{ cfm with safety factor of 10} \quad (10-5) \end{aligned}$$

This example is based on the presence of toluene in a coating. Other solvents or complex blends of solvents commonly found in coatings may yield different vapor volumes per gallon of liquid coating. Currently, CWGS 09940 requires 140 m³ per minute (5,000 cfm) of air per spray gun, independent of the solvent type/blend in the coating.

(c) Fire protection/prevention. Most solvent-borne coatings and thinners are highly flammable in liquid form. Concentrated vapors in sufficient volume also are explosive in an enclosed area. As a result, the engineer should recognize that proper storage and handling of flammable or combustible liquids is an integral part of fire protection/prevention. Provisions for bulk storage areas and paint/solvent storage containers will be discussed.

(1) Bulk storage areas. OSHA has established regulations that control the storage and use of flammable and combustible liquids in both the Construction and General Industry Standards. These are published in the

Code of Federal Regulations (CFR) Title 29, Part 1910, Section 106 (29 CFR 1910.106) of the Safety and Health Rules for General Industry. Basically, these regulations state that the quantities of flammable liquids and solvents must be limited, depending on the location of the storage area, its construction, and the fire prevention measures available. OSHA Construction Industry Standard 1926.152 simplifies the storage of containers of flammable or combustible liquids by limiting the quantities of liquid to 4,158 L (1,100 gal) in any one area. Unlike the General Industry Standard, this OSHA Construction Industry Standard makes no distinction between the classes of liquids to be stored. The OSHA General Industry Standard applies to both indoor and outdoor storage of flammable and combustible liquids. The tables in the OSHA standard list the quantities (in gallons) permitted based on the NFPA class of liquid in use. Flammable and combustible liquid storage indoors is further limited, depending on the building level where materials are stored and whether or not the container piles are protected by fire sprinklers, heat-resistant walls, dikes, explosion-proof lighting, and ventilation. Most of the quantities listed in the OSHA standard are more than normally would be stored inside a simple box trailer typically found at a jobsite without fire protection. OSHA and the NFPA do not specifically address coating storage in trailers at a construction jobsite, so OSHA inspectors in various states may try to interpret these regulations differently. Therefore, flammable and combustible liquids should always be safely and properly used and stored at a jobsite. The following items should be established to improve trailer storage of flammable and combustible coatings and solvents at a jobsite.

- Most coatings emit vapors heavier than air in a closed trailer; therefore, ventilation screens should be placed at floor level at each end of the trailer in case there is a leak or spill.
- A heavy steel industrial cabinet should be used to store aerosol spray cans within the trailer; these cans become flaming airborne rockets when on fire and can spread a small fire throughout the trailer unless contained.
- At least one fire extinguisher with a rating of not less than 20-B units must be placed outside, in the open, no closer than 3 meters (10 feet) from the trailer.
- No more than 4,158 L (1,100 gal) total are permitted in any one outdoor storage area, and containers are not permitted to exceed 226.8 L (60 gal) each.
- The storage trailer should not be closer than 6 meters (20 feet) to a building.

- Coating mixing should be done only outside the storage trailer.
- Only air-operated agitators or inherently safe electric mixers should be used for mixing to prevent spark generation.

(2) Storage containers and safe work practices. Even though the quantities of flammable and combustible liquids stored on site are within OSHA guidelines, safe practices for dispensing and handling must be followed. Combustible and flammable liquids form vapors that can be ignited by sparks, open flames, or static electricity.

(a) Dispensing a flammable liquid from a drum to a smaller container causes static electrical charges to be generated. If a static discharge occurs, the flammable vapor present near the container can ignite explosively; an ignition can be prevented by electrically bonding the receiving container to the drum to draw off any static electrical charge on the container generated by the liquid flow, and to pass it harmlessly into the grounding system. Bonding is accomplished with a special bonding wire connected to the drum and clamped to the receiving container.

(b) In addition to this bond connection, drums must be properly grounded to the earth to safely drain static charges. When flammable or combustible liquids are dispensed from a 208-L (55-gal) drum in the horizontal position, each drum should be fitted with a self-closing valve and vacuum relief vents. Drum pumps can be used and are preferred to dispense flammable liquids from drums in the upright position. Drip cans should be positioned below each drum faucet to catch spills or leaks from worn or damaged faucets. These cans are lidless and have a perforated fire baffle over the opening. Bonding and grounding wires must be in place.

(c) Underwriters Laboratories listed or Factory Mutual approved safety cans must be used to transport flammable liquids from the storage area to the jobsite. These cans (metal or nonmetallic) must be labeled and must be leak tight. They also must automatically vent vapors when the pressure rises above 34.45 kPa (5 psi), have flame-arresting screens to prevent fire from reaching the contents, and have an automatic closing spout cap. The maximum allowable size of container depends on what class of flammable liquid will be stored and the type of material the container is made of.

d. Material safety data sheet (MSDS).

(1) The MSDS is an informational sheet required by the OSHA Hazard Communication Standard 29 CFR 1926.59 for each coating material, thinner, or other chemical stored

at the jobsite. An MSDS must be provided with each shipment of chemicals received at the site. The MSDS can be used for several purposes such as:

- Identifying chemical ingredients in coating materials.
- Assessing technical data like flash point, LEL, OSHA PEL, odor, and health hazards.
- Selecting proper personal protective equipment.
- Establishing proper storage practices.
- Measures to take to clean up spills or leaks.

(2) The MSDS must be easily accessible and must be available for viewing without request for permission. The MSDS must be current, and the worker must be instructed on how to read and interpret the information on the MSDS.

10-3. Hand and Power Tools

a. All hand and power tools should be kept in good repair and used only for the purpose for which they were designed. The most common injuries resulting from the use of power tools include burns, cuts, electric shock, particles in the eye, and trips/falls due to flexible hoses, cords, and cables in walking areas. Loose clothing or jewelry should not be worn because they may be caught in the power tool.

b. Power tool cleaning equipment such as the roto-peen and needle gun generate noise levels in excess of the OSHA permissible limit of 90 decibels. Therefore, hearing protection should be worn when using power tool cleaning equipment. In addition, the use of eye protection is required when machines or operations present the hazard of flying objects or liquids. Eye protectors that fit snugly and do not impede the wearer should be worn when removing coatings with hand or power tools. Eye protection must be designed, constructed, tested, and used in accordance with the American National Standard for Occupational and Educational Eye and Face Protection Z87.1-1968.

10-4. Abrasive Blast-Cleaning Equipment

The primary hazards associated with abrasive blast cleaning are created by the high air pressures needed to propel an abrasive agent at high velocities toward a surface. This paragraph will cover safety hazards associated with blast-cleaning equipment.

a. Nozzles. Nozzles come in a variety of sizes, lengths, and liner materials. Prior to use, the liner material should be carefully inspected for wear or surface fractures.

Blasters are often careless in the handling of nozzles: dropping them to the ground, using them as signal hammers, and losing the gasket between the nozzle and the nozzle holder. A broken liner can be shot out of a nozzle, bounce off the surface being cleaned, and injure the blast operator. Most nozzle manufacturers recommend replacing nozzles when the orifice is 3.175 mm (2/16 in.) larger than the original size, or if the liner appears cracked. The nozzle threads also should be checked for wear.

b. Deadman control. According to current OSHA standards (29 CFR 1926.302) all blast-cleaning machines must be equipped with "deadman" controls to protect the user. These are remote control systems that automatically shut off the blast machine when the operator releases a handle. This system usually is a spring-loaded control located near the nozzle end of the blast hose. When depressed, the flow of high pressure air and abrasive is started. When released, the flow is stopped.

c. Blast pots or pressure blast tanks.

(1) Blast pots and related pressure tanks for blast-cleaning operations must be built to standards set by the American Society of Mechanical Engineers (ASME). Pots not meeting these requirements must not be used. A pressure vessel meeting the ASME code will be labeled indicating that it has been built and tested to withstand the pressures used in field blasting operations. Unless otherwise specified by the manufacturer, the maximum working pressure of blast machines and related components must not exceed the ASME approved limit of 861.25 kPa (125 psi). The blast machine should be electrically connected to ground to help eliminate static electricity hazards. The ASME code prohibits any field welding or alterations to the pressure vessel.

(2) Pressure tanks for compressed air or blast pots under pressure should be checked regularly because these containers also are subject to abrasion and deterioration beyond that of normal pressure vessels. Pressurized abrasive tanks must have a removable plate for internal inspection. The blast system must be depressurized before opening any doors, panels, or lids. The manufacturer's instructions to maintain equipment at recommended intervals always should be followed.

d. Pot tender. The pot tender is responsible for maintaining the blast machine in support of the blasters. If the pot tender cannot see the blasters, a means of communication should be established. This may be two-way radios or a signal man, which allows for immediate shut down of equipment if there is an equipment failure or other problem.

e. External couplings and blast hose.

(1) Only externally fitted quick couplings should be used on blast hoses. Internal fittings can reduce the inside diameter and the air-carrying capacity of the hose by more than 50 percent. This reduction in the inside diameter of the hose sets up a turbulent condition in which the air and abrasive strike the leading edge of the nipple inside of the hose and create tremendous pressure drops and a heavy wear condition at this point. Most commercially available external couplings are equipped with sled-like runners so the coupling will not catch if it is dragged over irregular surfaces such as steel decking.

(2) When repairing a blast hose or installing hose couplings, the end of the hose should be cut square for proper fit in the coupling. An irregular or nonsquare cut will lead to a potential wear area between the end of the hose and the inside of the coupling or nozzle holder. Safety pins should be installed at every coupling connection to prevent accidental disengagement during use or hose movement. Safety cables also should be used at all air hose and blast hose coupling connections. These cables relieve tension on the hose and help control whipping action if there is a coupling blowout.

(3) The blast hose should be a natural gum tube treated with carbon black to prevent electrical shock to the operator.

(4) Proper care of blast hoses is essential. Hoses should be stored in dry areas to prevent rotting. During blast-cleaning operations, the hose should run as straight as possible. If the hose must curve around an object, a long radius curve should be used; sharp curves create rapid interior wear on the hose.

f. Helmets.

(1) The dust produced by abrasive blasting is a serious health hazard. The dust results from the breakdown of abrasives and the pulverizing of surface coatings, rust, mill scale, and other materials on the steel surface that is being blast cleaned. To protect workers from this dust, constant flow, air-fed blast helmets are used. The supplied-air system must meet the requirements established by NIOSH for type C respirators. Type C constant-flow air systems for abrasive blasting operations are classified further by NIOSH as Type CE respirators. Type CE systems are specifically designed for abrasive blasting work because they include protection for the head, neck, and upper body. The primary components of the system include: an air source (compressor), a delivery system (hoses, air filters, pressure regulator), and a NIOSH/MSHA (Mine Safety and Health Administration) approved blasting hood/helmet (with airflow control valve and belt clip) that maintains a minimum

airflow of 0.167 m³/min (6 cfm) and a maximum airflow of 0.42 m³/min (15 cfm) to the hood.

(2) OSHA requires that the blasting hood be supplied with air meeting the requirements for Grade D air, as described by the Compressed Gas Association Specification G7.1, which was updated in 1989. The requirements for meeting Grade D breathing air are listed in Table 10-1.

Table 10-1
Grade D Breathing Air Requirements

Oxygen	19.5 to 23.5 percent
Oil mist	5 mg/m ³ or less
Carbon monoxide	10 ppm or less
Carbon dioxide	200 to 1,000 ppm
Odors	None perceived

Only breathing-air-type compressors should be used. They should be equipped with in-line air-purifying sorbent beds and filters, compressor failure alarm, high temperature alarms, and pressure regulators to the respirator air lines. Breathing air couplings shall be incompatible with outlets for nonrespirable air or other gas systems to prevent inadvertent servicing of air-line respirators with nonrespirable gases. Oil-lubricated compressors also should be equipped with a carbon monoxide alarm or they should be tested frequently to ensure that carbon monoxide levels remain below 10 ppm. Compressors should be situated to avoid entry of contaminated air into the system.

g. Protective clothing. In addition to respiratory protective equipment, blasters should wear apparel to prevent damage to their skin from abrasive blast-cleaning material and ricocheting. This includes safety footwear meeting the requirements of ANSI Z41, coveralls, leather or rubber capes, and gloves. Pants and sleeve cuffs should be secured with tape or other suitable fasteners.

10-5. Spray Equipment

a. Respiratory protection. Spray painting has the capability to release high concentrations of solvent vapors in a short period of time. Therefore, adequate ventilation is necessary to provide a safer work environment. (For a more detailed discussion of ventilation systems, see paragraph 10-5c.) When ventilation cannot maintain worker exposures to potentially harmful vapors within permissible exposure limit (PEL), respiratory protection needs to be provided. An overview of the requirements established by

OSHA for properly selecting, using, and maintaining respirators is discussed in paragraph 10-7.

b. Spray gun operations. Because airless spray systems operate at pressures in the range of 13,780 to 20,670 kPa (2,000 to 3,000 psi), safety considerations require special attention during operation. A tip guard and trigger lock must be on all airless spray guns to prevent injury to the worker. The extremely high fluid pressure developed in airless spray coating equipment causes a powerful stream of coating to be discharged for some distance. This pressure remains in the system even though the pump has been shut off, and the pressure can be relieved only by being discharged through the gun. Fluid sprayed from the gun is propelled with sufficient force to penetrate the skin and cause serious damage. The entire system is pressurized so a rupture or leak in the hose at the fittings can result in dangerous high pressure spray.

c. Ventilation.

(1) Good ventilation is essential when painting in enclosed areas. This usually is achieved by introducing "fresh" outside air into the painting area. All areas of the enclosed space should be swept by moving air. The volume of air needed to dilute vapors below their lower explosive limit is discussed in paragraph 10-2. A mechanical engineer familiar with design of ventilation systems may be required to ensure proper distribution of airflow through the space. In enclosed spaces, solvent vapors tend to concentrate at floor level. Therefore, ventilation systems should be designed to exhaust air from the lower portions of the enclosure. Make-up air should be introduced into the enclosure near the upper portions of the space and on the opposite side from which the exhaust is located. This will allow for a more even distribution of outside air through the enclosure. The ventilation must continue throughout the drying process.

(2) Although not applicable to most field painting operations, some spray application methods are performed using principles of local exhaust ventilation. Local exhaust ventilation (e.g., spray booth) is designed to remove the paint mist and vapors near their point of generation. Air velocity through the spray area and in the ductwork must be adequate to direct paint mist and vapors into the exhaust system. The American Conference of Governmental Industrial Hygienists (ACGIH) published a manual on industrial ventilation (ACGIH 1989). This manual recommends criteria for duct velocities and airflow through spray coating booths. For example, very fine, light dusts require a duct velocity of 610 meters per minute (m/min) (2,000 feet per minute [fpm]), and heavy or moist dust requires a duct velocity of 1,372.5+ m/min (4,500+ fpm).

A spray coating operation requires a duct velocity of 2,000 fpm. For walk-in type spray booths, the ACGIH recommends an air velocity of 30.5 m/min (100 fpm) at the face of the booth.

10-6. Welding and Cutting of Coated Steel

a. A major hazard results from welding and cutting on surfaces coated with lead-based finishes. If possible, these coating materials should be removed mechanically by scraping, wire brushing, or blasting before welding or cutting. If this is not possible, local exhaust ventilation or respiratory protection must be used to protect the worker during welding and cutting.

b. OSHA standard 29 CFR 1926.354 addresses controls for this type of work in enclosed spaces and in open air. In enclosed spaces, all surfaces covered with a preservative coating that contains a toxic constituent such as lead must be stripped of that toxic coating for a distance of at least 101.6 mm (4 in.) from the area of heat application, or the employee must be protected by an air-supplied respirator. During welding and cutting work in open air, employees only need to be provided with a respirator adequate for the airborne level of exposure of the toxic constituent.

10-7. Respiratory Protection Overview

OSHA has established PEL for approximately 500 chemical substances. If workers are exposed to any one of these substances in excess of permissible limits, the employer is required to provide respiratory protection until feasible engineering controls can be implemented to reduce exposure levels. To ensure the proper use of respirators, OSHA requires the employer to provide a minimal acceptable respiratory protection program, as detailed in OSHA's respiratory protection standards 29 CFR 1926.103 and 1910.134. The following paragraphs outline the primary requirements of these standards.

a. Employee qualifications.

(1) Medical surveillance. Wearing any type of respirator imposes some physiological stress on the wearer. If the worker's cardiovascular or pulmonary function is significantly impaired, wearing a respirator could constitute an unacceptable risk. OSHA requires that persons should not be assigned to tasks requiring use of respirators unless it has been determined by a physician that they are physically able to perform the work and use the respiratory equipment. The physician will determine what health and physical conditions should be evaluated. The respirator user's medical status must be reviewed annually. The types of information generally included in the respirator user's

medical evaluation include: respiratory system evaluation (pulmonary function test), cardiovascular evaluation, history of respiratory disease, work history to identify previous chemical exposures, any other medical information that might affect the worker's ability to wear a respirator.

(2) Training. In addition to ensuring that workers required to use a respirator are medically qualified to wear the device, the worker also must be trained on the proper use of the equipment. A good training program for workers assigned to wear a respirator includes:

- Opportunity to handle the respirator.
- Proper fitting, including demonstrations and practice in wearing, adjusting, and determining the fit of the respirator.
- Test of facepiece-to-face seal.
- A familiarization period of wear in normal air.
- Wearing the respirator in a test atmosphere, such as during a fit test.
- Explanation of the nature of the respiratory hazard and what happens if the respirator is not used properly.
- Explanation of why a particular type of respirator has been selected, and its limitations.

(3) Fit testing. Workers assigned to wear an air-purifying type of respirator should receive fitting instructions and a fit test. The check must include demonstrations and practice in how to inspect, adjust, and wear the respirator. After successful completion of the fit check, the individual should pass a fit test. Two types of fit tests are acceptable to OSHA: qualitative and quantitative. A qualitative test relies on the wearer's subjective response to an irritant smoke or an unpleasant odor. A quantitative test is an actual measure of the protection provided by the respirator in a known concentration of a test atmosphere. Regardless of the type of test performed, the fit test should be documented, including the type of respirator, manufacturer, model of respirator, size of the mask, fit test results, date test was administered, and employee signature.

(4) Facial hair. Hair in the face-seal area of a respirator causes a significant decrease in the protection factor provided by either an air-supplied or air-purifying respirator. The amount of leakage in the face seal varies with the type or texture of facial hair. A fine-haired beard usually will compact and cause less leakage than a coarse-haired beard. However, any hair in the face-seal area will decrease the

amount of personal protection a respirator is designed to provide. For this reason, OSHA regulations prohibit any hair in the facepiece sealing area. The rule of thumb is no more than one day's growth of facial hair.

(5) Corrective lenses. When a respirator user must wear corrective lenses, the respirator must be fitted to provide good vision and should not interfere with the seal of the respirator when in use. Glasses with straps or temple bars that pass through the sealing surface of air-purifying or air-supplied, tight fitting, full-facepiece respirators should not be used. Systems have been developed for mounting corrective lenses inside respirators. Mounting of corrective lenses to the facepiece should be conducted by a trained individual to provide good vision and comfort to the wearer. Contact lenses should not be worn in conjunction with a respirator. Contaminants may get into the eyes and cause severe irritation and/or discomfort with half-masks. A full facepiece can pull at the side of the eye and pop out the lens.

b. Respirator selection.

(1) Choosing the right equipment involves several steps: determining the hazard and its extent, choosing equipment that is certified for the function, and assuring that the device is performing the intended function. The proper selection of respirators must be made according to the guidance of ANSI Z88.2 or "NIOSH—Respirator Decision Logic."

(2) Chemical and physical properties of the contaminant, as well as the toxicity and concentration of the hazardous material and the amount of oxygen present, must be considered in selecting the proper respirators. The nature and extent of the hazard, work rate, area to be covered, mobility, work requirements and conditions, and the limitations and characteristics of the available respirators also are selection factors.

(3) There are two basic classes of respirators: air purifying and air supplying. Air-purifying respirators use filters or sorbents to remove harmful substances from the air. They range from simple disposable masks to sophisticated powered air-purifying respirators. Air-purifying respirators do not supply oxygen and may not be used in oxygen-deficient atmospheres or in atmospheres that are immediately dangerous to life or health. Atmosphere-supplying respirators are designed to provide breathable air from a clean air source. They range from supplied-air respirators and self-contained breathing apparatus (SCBA) to complete air-supplied suits.

(4) Air-purifying respirators present minimal interference with the wearer's movement. Atmosphere-supplying respirators may restrict movement and present potential

hazards. For example, supplied-air respirators with their trailing hoses can limit the area the wearer can move to and may present a potential hazard when the trailing hose can come into contact with machinery. Similarly, a SCBA respirator that includes a back-mounted, compressed-air cylinder presents both a size and weight penalty that may restrict climbing and movement in tight places.

(5) The protection factor assigned to the respirator by NIOSH is another consideration in selecting the proper respirator. A protection factor is a measure of the degree of protection afforded to the respirator wearer by that respirator. The protection factor may change depending on the chemical substance. The NIOSH assigned protection factor can be obtained from the respirator manufacturer; it usually is typed on the box containing the respirator. Protection factors can be used to determine the maximum allowable airborne concentration of a contaminant that the respirator is approved for. For example, the maximum allowable use concentration equals the NIOSH assigned protection factor for the respirator multiplied by the PEL for the contaminant.

c. Respirator issuance. Respirators should be issued only to employees who meet the qualifications outlined previously. Only properly selected respirators that provide an adequate degree of protection should be issued. Employees should not be permitted to use a respirator that has not been approved by the employer.

d. Respirator use. The respirator manufacturer's instructions should be read to understand the equipment's purpose and its limitations. The respirator must be worn in the manner in which it achieved NIOSH approval. All respirators must be inspected for wear and deterioration of their components before and after each use. Special attention should be given to rubber or plastic parts, which can deteriorate. The facepiece—especially the face seal surface, headbands, valves, fittings, and cartridges—must be in good condition. A respiratory protection program as required by OSHA (see Chapter 11) must be established; this program must describe cleaning, storage, and inspection practices.

10-8. Confined Space Entry

In 1993, OSHA issued a standard that dealt with working in confined spaces. The 29 CFR 1910.146 standard defines confined space as a space that is large enough and so configured that an employee can bodily enter and perform assigned work, has limited or restricted means for entry or exit, and is not designed for continuous employee occupancy. EM 385-1-1 also adds that a confined space may be defined as a space having unfavorable natural

ventilation that could contain or has produced dangerous concentrations of airborne contaminants or asphyxiants.

a. Confined space program.

(1) In their definition of confined spaces found in 29 CFR 1910.146, OSHA includes both hazardous and nonhazardous spaces. In some situations, a space may be considered a nonpermit confined space. Nonpermit confined space means a confined space that does not contain or, with respect to atmospheric hazards, have the potential to contain any hazard capable of causing death or serious physical harm. Confined spaces may be entered without the need for a written permit or attendant if the space can be maintained in a safe condition for entry by mechanical ventilation alone. Permit-required, confined spaces are defined as any area presenting, or having the potential for containing, hazards related to atmospheric conditions, engulfment, configuration, or any other recognized serious hazard.

(2) To work in a permit-required confined space, the employer is required to have a written program. The written confined space program must:

- Prevent unauthorized entry.
- Identify and evaluate permit space hazards prior to entering.
- Describe the means, procedures, and practices for safe entry, including air testing.
- Provide specified equipment for entry, including personal protective equipment such as respirators, maintain the equipment, and ensure its proper use. Retrieval systems must be used when an individual enters a permit-required space to facilitate nonentry rescue, unless the retrieval equipment increases the risk of entry or would not contribute to the rescue.
- Designate the persons with active roles in entry operations (e.g., entrants, attendants).
- Describe the procedures for summoning rescue and emergency services and preventing unauthorized personnel from attempting a rescue.
- Describe the system for preparation, issuance, use, and cancellation of entry permits.
- Describe the procedures to coordinate entry operations when employees of more than one employer are working in a permit space.

- Require the review of the permit-required, confined space program within 1 year of entry, which would result in an annual review for employers who have at least one permit space entered each year.

b. Confined space hazards.

(1) The hazards associated with confined spaces include hazardous atmospheres and physical hazards. A hazardous atmosphere is an atmosphere that may expose employees to the risk of death, incapacitation, impairment of ability to self-rescue (that is, escape unaided from a permit space), injury, or acute illness from one or more of the following causes.

(a) Flammable gas, vapor, or mist in excess of 10 percent of its LEL. When vapors of a flammable liquid are mixed with air in the proper proportions in the presence of a source of ignition, rapid combustion or an explosion can occur. This proper proportion is called the flammable range and is often referred to as the explosive range. The flammable range includes all concentrations of flammable vapor or gas in air in which a flash will occur or a flame will travel if the mixture is ignited.

(b) Airborne combustible dust at a concentration that meets or exceeds its LEL.

(c) Atmospheric oxygen concentration below 19.5 percent or above 23.5 percent. An oxygen-deficient atmosphere is an atmosphere containing less than 19.5 percent oxygen by volume. The normal percentage of oxygen in air is approximately 20.9 percent.

(d) Atmospheric concentration of any substance for which a dose or a PEL is published in Subpart Z, Toxic and Hazardous Substances of 29 CFR 1910, and which could result in employee exposure in excess of its dose or PEL. An example of chemical substances found in Subpart Z that are common to painting include acetone, toluene, some ketones, and other solvents.

(e) Any other atmospheric condition that is immediately dangerous to life or health. An immediately dangerous to life and health atmosphere is defined as any condition that poses an immediate or delayed threat to life, that would cause irreversible adverse effects, or that would interfere with an individual's ability to escape unaided from a permit space.

(2) There are many safety hazards beyond atmospheric conditions that must be evaluated before permitting entry into a confined space. This includes physical hazards such as moving agitators, gears, and pistons that activate or move as a result of stored energy. This equipment must be

blocked, braced, or chained, then locked out and tagged out to prevent accidental activation or unexpected movement.

(3) Valves and pipelines leading to a confined space also must be deactivated and tagged to prevent gases or liquids from entering that could explode, poison, burn, or drown a person. Valves should be chained or locked in the closed position. Pipelines should be disconnected, blanked off, and bled to empty out chemicals in the pipes.

(4) Noise also can be a hazard in a confined space where it is intensified, resulting in the workers not being able to hear important warnings or directions. Electronic communications and earphones may be necessary in noisy, confined areas.

(5) Heat can build up rapidly in a confined space and cause cramps, heat exhaustion, or heat stroke. Fresh air ventilation and cooling vests may be used to lessen the risks.

c. Self-contained breathing apparatus. SCBA may be one of the most important pieces of respiratory protective equipment used during emergencies and rescue attempts from confined spaces. The OSHA standard permits employers to have their own rescue team, or they may rely on offsite rescue services. The law requires the employer to ensure that the rescue team (in-house) or the rescue service (offsite) is provided with, and is trained to use, personal protective equipment (i.e., SCBA) and equipment necessary for making rescues. The rescue team or service must be capable of responding within 5 minutes of notification.

d. Standby person. A standby person is an individual stationed outside a permit-required confined space. This individual is assigned the responsibility of monitoring the workers authorized to enter the space and perform all duties assigned in the written confined-space program. OSHA refers to this person as an attendant. The person must be knowledgeable of the hazards associated with the confined space, be aware of the possible behavioral effects of exposure to any atmospheric hazards, maintain an accurate count of the number of workers in the space, remain outside the space while it is occupied, and establish a communication system to monitor workers inside and alert them to the need to evacuate the space.

e. Training. Each employee assigned to work in a confined space must be trained prior to being assigned duties, before there is a change in their duties, or whenever there is a change in the permit space operations for which the employee has not been trained. The training must allow the employee to acquire the understanding, knowledge, and

skills necessary to perform duties safely. The employer is required to certify that the training has been accomplished. The certification must contain the employee's name, signature or initials of the trainer, and dates of training.

f. Ventilation equipment. Mechanical ventilation systems circulate fresh air throughout a confined space. The supply air fan should be located in an area that does not draw contaminated air into the confined space. Supply air fans should not be located near exhausts from gasoline or diesel powered equipment. The mechanical ventilation should remain in place the entire time the space is occupied. The standby person should test the atmosphere from outside the space periodically to ensure that no problem develops as a result of maintenance work performed in the space.

g. Atmospheric testing. Test equipment must be calibrated prior to use. Tests should be performed for oxygen content, flammable gases and vapors, and other potential toxic air contaminants such as carbon monoxide, hydrogen sulfide, aromatic hydrocarbon, and ammonia. The test for oxygen should be performed first because most combustible gas meters are oxygen dependent and will not

provide reliable readings in an oxygen-deficient atmosphere. Combustible gases then are tested because, in most instances, the threat of fire or explosion is both more immediate and more life threatening than exposure to toxic gases and vapors. If necessary, tests for toxic gases are performed last. Atmospheric testing of the confined space usually is performed from top to bottom to allow time for each sample to reach the sensors in the equipment. The atmosphere within the space must be tested periodically as necessary to ensure that the continuous forced air ventilation is preventing the accumulation of a hazardous atmosphere. For permit-required spaces, continuous forced air ventilation must be used the entire time the space is occupied.

h. Entry permit. The OSHA standard requires a supervisor to authorize entry by preparing and signing a written permit. Permits must be available to all employees and extend through the duration of the project. The permit should be reauthorized by the supervisor for each work shift. The permit must be posted near the confined space for immediate reference. The OSHA confined space regulation (29 CFR 1910.146) specifies what must be documented on the permit.

Chapter 11 Environment and Worker Protection Regulations

11-1. Introduction

This chapter provides information on the controls necessary for environmental protection during paint removal operations. Details on the Federal regulations and a discussion of the means for complying with them are given. Note that state and local regulations can be more restrictive than the Federal regulations and must be researched before undertaking a paint removal project. Also be aware that the Government is responsible for assuring compliance with these regulations.

11-2. Development of Environmental and Worker Protection Regulations

a. Legislation passed by Congress is termed an Act of Congress. The responsibility for developing rules or regulations to implement the requirements of the Acts is given to various agencies of the Federal Government such as OSHA or USEPA. The proposed regulations developed by these agencies are published daily in the Federal Register; after publication, the public is permitted to review and comment on the proposed regulations. All comments are evaluated after the specified review time (30 days, 60 days, etc.) has passed. The comments may or may not result in changes to the proposed regulations, which are published in the Federal Register as the final rules.

b. The final rules from the Federal Register are compiled annually in the Code of Federal Regulations (CFR). The CFR is divided into 50 titles, numbered 1 through 50, which represent broad areas subject to Federal regulation. For example, Title 29 "Labor" contains the OSHA standards that govern the protection of workers; and Title 40 "Protection of the Environment" contains the USEPA regulations for the protection of the environment. Most CFRs applicable to industrial painting are updated every July 1; and, although they carry a July 1 date, typically are not printed and available until October or November of each year. References to the CFR's are made throughout this chapter. Copies of CFR's are not appended, but can be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

c. The general format for identifying a specific regulation in the CFR involves the use of a combination of numbers and letters. For example, 40 CFR 50.12, "National Primary and Secondary Ambient Air Quality Standards for OSHA Lead" indicates that the regulation is found in

Title 40 of the CFR. It is further identified as part 50 (a part covers a specific regulatory area and can range in length from a few sentences to hundreds of pages). The number 12 that follows the decimal point indicates a given section where the specific information is found. A section also may range in length from a few sentences to many pages. Although not shown in this example, the section number may be followed by a series of letters and numbers in parentheses to further identify individual paragraphs.

d. The regulations discussed in this chapter are current at the time (1994) of writing. However, new regulations are being proposed and promulgated continuously. In addition, state or local regulations may be more restrictive than the Federal regulations and must be reviewed carefully before undertaking a project.

11-3. Worker Protection

Worker safety for general painting activities is discussed in Chapter 10. The requirements discussed in Chapter 10 are applicable to lead paint removal, but a number of specialized worker protection issues must be addressed as well. When outside contractors are used, they should provide plans and programs to address the appropriate items in this section. For in-house work, the facility owner should address these items for the protection of the owner's workforce. The determination of worker protection requirements for a specific jobsite must be guided by Federal requirements established under OSHA 29 CFR 1926.62, which became effective June 3, 1993. The development of the Interim Final Rule was mandated by Congress through Title X of the Housing and Community Development Act of 1992. A "Final" Comprehensive Health Standard for Lead in Construction at the state or Federal level has yet to be finalized. However, 29 CFR 1926.62 carries the full force of law and is enforceable in all states. Pertinent sections of 29 CFR 1926.62 are discussed below.

a. Action level/missible exposure limit.

(1) The OSHA 1926.62 standard requires that employers ensure that no employee is exposed to lead at concentrations greater than $50 \mu\text{g}/\text{m}^3$ of air averaged over an 8-hour period. This level is defined as the Permissible Exposure Limit (PEL). If an employee is exposed to lead for more than 8 hours in any work day, provisions are included for reducing the PEL for that day. The PEL (employee's allowable exposure) as a time weighted average (TWA) is reduced according to Equation 11-1.

$$\text{Adjusted PEL } (\mu\text{g}/\text{m}^3) = \frac{400}{\text{hr in work day}} \quad (11-1)$$

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For example, for a 10-hour work day, the PEL is reduced to $40 \mu\text{g}/\text{m}^3$.

(2) The 29 CFR 1926.62 standard also established an action level at $30 \mu\text{g}/\text{m}^3$. This action level is the airborne concentration where certain provisions of the 29 CFR 1926.62 standard are invoked such as blood lead analysis, training, and hand washing facilities. Many of the provisions of 29 CFR 1926.62 apply if the exposure is below the action level. When respirators are used, the employee exposure for the periods in which the respirator is worn may be averaged with the exposure levels during the periods when respirators are not worn to determine the daily TWA exposure. For example, if the airborne concentration of lead in a work area is $500 \mu\text{g}/\text{m}^3$ and the employee works for 4 hours in this area while wearing a half-mask respirator, the exposure during the 4 hours is $50 \mu\text{g}/\text{m}^3$ (the protection factor of a half-mask respirator is 10, resulting in the employee exposure of $50 \mu\text{g}/\text{m}^3$). If the remaining 4 hours are spent away from any lead exposure, and a respirator is not needed for any other purpose, the exposure for the remaining 4 hours is $0 \mu\text{g}/\text{m}^3$. The TWA exposure for the day is $25 \mu\text{g}/\text{m}^3$.

b. Exposure assessment.

(1) This section of 29 CFR 1926.62 requires that the employer initially establish whether the work environment (i.e., work activity) will result in an employee exposure to lead at or above the action level. This is accomplished by:

(a) Compiling exposure data the employer has collected within the past 12 months for similar operations conducted under similar work place conditions, environmental conditions, and work practices;

(b) Through objective data, demonstrating that the operation or activity cannot result in employee exposure at or above the action level; or

(c) Conducting monitoring consisting of personal samples representative of a full shift of the employee's regular, daily exposure to lead.

(2) When exposure monitoring is undertaken, at least one sample for each job classification in each work area is required for each shift (or for the shift with the highest exposure level). However, there are provisions in OSHA 1926.62 for reducing the initial determination to only a representative sample of employees reasonably believed to be exposed to the greatest airborne concentrations of lead (e.g., those conducting the abrasive blast cleaning) rather than for each job classification. But, if the initial limited determination shows the possibility of employee exposure at or above the action level, more extensive monitoring of each

job classification per shift is required.

(3) If the initial monitoring involves only the abrasive blast cleaners and the results are above the action level, representative monitoring of the exposure for each job classification (e.g., pot tenders, cleanup personnel, painters, etc.) must be conducted. Because industrial lead paint removal frequently leads to exposures well above the action level, employers often conduct the initial monitoring on all job classifications at the same time rather than monitoring only the expected highest exposures first.

(4) If the initial monitoring indicates that the exposure of all employees is below the action level, further monitoring need not be repeated unless there is a change in equipment, processes, control methods, or personnel or a new task is undertaken that may result in additional employees being exposed to lead at or above the action level.

(5) If the initial or subsequent determinations reveal employee exposure to be at or above the action level, but at or below the PEL, monitoring must be performed at least every 6 months and continued until at least two consecutive measurements, taken at least 7 days apart, are below the action level. At that time, monitoring can be discontinued unless any of the changes in work activities occur as discussed here.

(6) If the initial determination reveals exposure to be above the PEL, the monitoring is repeated at least quarterly. The quarterly monitoring continues until at least two consecutive measurements, taken at least 7 days apart, are at or below the PEL or below the action level, at which time the monitoring frequencies described here apply.

(7) Employees must be notified of all monitoring results within 5 working days after completion of the assessment. The results include the date of the determination, location of monitoring within the work site, and the name and social security number of each employee monitored. When the results are above the PEL, a statement must be included that the exposure was at or above that level as well as a description of the corrective action that was or will be taken to reduce the exposure.

(8) The method of monitoring used to determine the level of lead in the work environment requires attaching a portable, battery-operated pump to the worker's belt. A hose connects the pump to a filter positioned in the worker's breathing zone but outside any respiratory protective device. The pump draws air across the filter at a known rate to collect airborne particulate within the breathing zone throughout the work shift. The filter is removed and analyzed by a qualified laboratory in accordance with

NIOSH Method 7082, to determine the lead exposure.

(9) The monitoring can be conducted by a competent person, but it is recommended that the monitoring protocol and test results be reviewed by a certified industrial hygienist (CIH), certified by the American Board of Industrial Hygienists.

(10) The OSHA 29 CFR 1926.62 standard includes special provisions for the protection of employees during the time the initial monitoring of the exposures is undertaken. The OSHA standard divides work tasks into three categories: those anticipated to result in exposures above the PEL, but not in excess of 10 times PEL ($500 \mu\text{g}/\text{m}^3$); those expected to be in excess of $500 \mu\text{g}/\text{m}^3$, but less than 50 times the PEL ($2,500 \mu\text{g}/\text{m}^3$); and those expected to be in excess of $2,500 \mu\text{g}/\text{m}^3$. Activities anticipated by the OSHA standard to fall within each of the categories for the purposes of initial protection follow.

(a) Up to $500 \mu\text{g}/\text{m}^3$ —manual demolition of structures with lead-containing coatings or paint (e.g., dry wall), manual scraping, manual sanding, heat gun applications, power-tool cleaning with dust collection systems, and spray painting with lead paint.

(b) Up to $2,500 \mu\text{g}/\text{m}^3$ —using lead-containing mortar, lead burning, or conducting the following activities where lead-containing coatings or paint are present: rivet busting, power-tool cleaning without dust collection systems, cleanup activities for which dry expendable abrasives are used, and the movement and removal of abrasives blasting enclosures.

(c) More than $2,500 \mu\text{g}/\text{m}^3$ —activities involving lead-containing coatings or paint on structures disturbed by abrasive blasting, welding, cutting, and torch burning.

(11) In each of the categories in paragraph 11-3b(10) above, the appropriate respiratory protection must be provided (with protection factors equal to or greater than 10X, 50X, and greater than 50X, depending on the exposure level). The OSHA 29 CFR 1926.62 standard requires additional protective measures as defined in a series of paragraphs (designated with lower case letters) throughout the standard. These measures include appropriate personal protective clothing and equipment used as described in paragraph (g); change areas and hand-washing facilities used as described in paragraph (i); biological monitoring made available in accordance with paragraph (j) consisting of blood sampling and analysis for lead and zinc protoporphyrin levels; and a certain level of the training required under paragraph (l). The training must include the portions of paragraph (l) which involve hazard communication (29 CFR 1926.59) and respiratory protection

(purpose, selection, fitting, use, and limitations). The training also must comply with 29 CFR 1926.21. After the results of the monitoring have been received, the respiratory and other protection requirements are modified accordingly.

c. Methods of compliance.

(1) The employer is required to implement engineering and work practice controls, including administrative controls, to reduce and maintain employee exposure to lead at or below the PEL. The OSHA 29 CFR 1926.62 standard indicates that these steps shall be taken to the extent such controls are feasible, although a definition of "feasible" is not provided. If the employee exposure is still above the PEL after all feasible engineering and work practice controls have been instituted, then (and only then) is respiratory protection used as described in paragraph (f) of the OSHA standard to ensure proper protection for the employee.

(2) The employer also is required to establish and implement a written compliance program prior to commencement of a project at which any employee may be occupationally exposed to lead at or above the PEL. The compliance program must include as a minimum the following.

(a) A description of each activity in which lead is emitted, including the equipment and materials involved, controls in place, crew size, employee job responsibilities, operating procedures, and maintenance practices.

(b) A description of the specific means used to control employee exposure to lead. When engineering controls are required, the engineering plans and studies used to determine the methods selected must be included. If mechanical ventilation is used to control lead exposure, the employer must evaluate its performance to maintain its effectiveness.

(c) A report of the technology considered in meeting the PEL.

(d) Air monitoring data that document the source of lead emissions.

(e) Detailed schedule for implementing the program.

(f) A work practice program that includes the protective work clothing and equipment to be used, housekeeping practices, and hygiene facilities and practices as well as other relevant work practices.

(g) An administrative control (job rotation) schedule, if appropriate, including the name and identification number of

each affected employee, the duration and exposure levels at each job where an employee is located, and any other information that may be useful in assessing the reliability of the administrative controls for reducing employee exposure to lead.

(h) A description of arrangements made among contractors on multicontractor sites with respect to informing other affected employees of potential lead exposures and the arrangements made for the respective responsibilities of the prime and/or subcontractor(s) for assuring full project compliance with the lead standard. Such arrangements are required in 29 CFR 1926.16 (e.g., the prime contractor may provide the shower facilities for use by all subcontractors).

(i) Other relevant information. The compliance program must provide for frequent and regular inspections by a competent person; the written programs must be available at the work site for examination and copying, and they must be completely accessible to any affected employee or authorized employee representative.

(3) The program is to be revised and updated at least every 6 months to remain current, and the employer also must ensure that employees follow good work practices such as those found in Appendix B of the OSHA 29 CFR 1926.62 lead standard.

d. Respiratory protection.

(1) The employer must provide respirators (at no cost to the employee) and ensure that they are used under the following circumstances.

(a) When the employee exposure to lead exceeds the PEL (even when engineering and work practices controls are used but are not sufficient to reduce exposures to below the PEL).

(b) When an employee requests a respirator.

(c) As the interim protection required for employees performing tasks identified in paragraph 11-3b while the monitoring is being undertaken.

(2) The respirator must be approved by MSHA and NIOSH.

(3) The respirator to be used is found in Table 11-1. The respirator is selected from Table 11-1 based on the airborne concentration of lead, although a powered, air-purifying respirator must be supplied in lieu of the respirator

specified in Table 11-1 if an employee chooses to use this type of respirator (if the powered air-purifying respirator provides adequate protection). The most significant impact of the information in Table 11-1 is that the traditional abrasive blasting helmet is stated to have a protection factor of 25X (up to 1,250 $\mu\text{g}/\text{m}^3$). Typical exposure in lead paint removal projects are many times in excess of this. (Note: ANSI Z88.2-1980 provided a protection factor of 1,000X for this same equipment.) An alternative to the traditional blasting helmet also is included in the Table 11-1. The type CE abrasive blasting respirator (full facepiece supplied air) operated in a positive-pressure mode is given a protection factor established of 2,000X the PEL.

(4) Employers are required to perform either qualitative or quantitative fit tests at the time of initial fitting of a respirator and at least every 6 months thereafter for each employee wearing a negative-pressure respirator. Appendix D of OSHA 29 CFR 1926.62 provides information on the qualitative fit tests (involving an odor or irritant smoke) which may be used only for half-mask respirators and quantitative fit tests. A quantitative fit test is required when other negative-pressure respirators are supplied (as full-face piece negative pressure). The quantitative fit test requires the use of a sophisticated machine to measure the amount of test material, if any, that leaks into the facepiece. It measures the protection factor for the respirator worn by the worker.

(5) If an employee exhibits difficulty breathing during the fitting test or during use, a medical examination in accordance with paragraph (j)(3)(i)(B) of OSHA 29 CFR 1926.62 shall be made available to the employee to determine whether the employee can wear a respirator while performing the required work activity.

(6) The employer also must institute a respiratory protection program in accordance with the following paragraphs of OSHA 29 CFR 1910.134: (b) "Requirements for a Minimal Acceptable Program," (d) "Air Quality," (e) "Use of Respirators," and (f) "Maintenance and Care of Respirators." Each employee must be permitted to change filter elements (when using a filter respirator) when an increase in breathing resistance is detected and be allowed to leave work areas to wash his face and the respirator facepiece when necessary to help prevent the skin irritation associated with its use.

(7) The respiratory protection program must include as a minimum the following:

(a) Written operating procedures for the selection and use of respirators.

Table 11-1
Respiratory Protection for Lead Aerosols^a

Airborne Concentration of Lead or Condition of Use	Required Respirator^b
Not in excess of 500 $\mu\text{g}/\text{m}^3$. (Protection - 10X)	<ul style="list-style-type: none"> • 1/2 mask air-purifying respirator with higher efficiency filters.^{c,d} • 1/2 mask supplied-air respirator operated in demand (negative pressure) mode.
Not in excess of 1,250 $\mu\text{g}/\text{m}^3$. (Protection - 25X)	<ul style="list-style-type: none"> • Loose-fitting hood or helmet powered air-purifying respirator with high efficiency filters.^d • Hood or helmet supplied-air respirator operated in a continuous-flow mode—e.g., type CE abrasive blasting respirators operated in a continuous-flow mode.
Not in excess of 2,500 $\mu\text{g}/\text{m}^3$. (Protection - 50X)	<ul style="list-style-type: none"> • Full facepiece air-purifying respirator with high efficiency filters.^d • Tight-fitting powered air-purifying respirator with high efficiency filters.^d • Full facepiece supplied-air respirator operated in demand mode. • 1/2 mask or full facepiece supplied-air respirator operated in a continuous-flow mode. • Full facepiece self-contained breathing apparatus (SCBA) operated in demand mode.
Not in excess of 50,000 $\mu\text{g}/\text{m}^3$. (Protection 1,000X)	<ul style="list-style-type: none"> • 1/2 mask supplied-air respirator operated in pressure demand or other positive-pressure mode.
Not in excess of 100,000 $\mu\text{g}/\text{m}^3$. (Protection 2,000X)	<ul style="list-style-type: none"> • Full facepiece supplied-air respirator operated in pressure demand or other positive-pressure mode—e.g., type CE abrasive blasting respirators operated in a positive-pressure mode.
Greater than 100,000 $\mu\text{g}/\text{m}^3$ unknown concentration, or fire fighting. (Protection over 2,000X)	<ul style="list-style-type: none"> • Full facepiece SCBA operated in pressure demand or other positive-pressure mode.

^a OSHA 29 CFR 1926.62.

^b Respirators specified for higher concentrations can be used at lower concentrations of lead.

^c Full facepiece is required if the lead aerosols cause eye or skin irritation at the use concentrations.

^d A high efficiency particulate filter (HEPA) means a filter that is 99.97 percent efficient against particles of 0.3 micron size or larger.

(b) Written verification that respirators are selected on the basis of the hazards to which the worker is exposed.

(c) Instruction and training on the proper use of respirators and their limitations (training must include fitting instructions and demonstrations on how the respirator is worn and adjusted and methods to determine if it fits properly).

(d) Regular cleaning and disinfecting of the respirators.

(e) Proper storage of respirators in convenient, clean, sanitary locations.

(f) Routine inspection of respirators during cleaning and replacement of worn and deteriorated parts.

(g) Appropriate surveillance of work area conditions and the degree of employee exposure.

(h) Regular inspection and evaluation of the program to determine its continued effectiveness.

(i) A physician's review to determine if the employee is physically able to conduct the work while using a respirator.

(j) The use of respirators approved only by MSHA and NIOSH.

e. Protective work clothing and equipment.

(1) The employer is required to provide (at no cost to the employee) and to ensure its use appropriate protective work clothing and equipment that prevents contamination of the employee and the employee's garments:

(a) When an employee is exposed to lead above the PEL,

(b) When an employee is exposed to lead compounds that may cause skin or eye irritations (e.g., lead arsenate, lead azide), and

(c) As an interim protection for employees performing the specific tasks identified in paragraph 11-3b(10) while the

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initial exposure monitoring is being undertaken.

(2) The clothing includes, but is not limited to, coveralls or similar full-body work clothing; gloves, hats, shoes, or disposable shoe coverlets; and face shields, vented goggles, or other appropriate protective equipment that complies with OSHA 29 CFR 1910.133.

(3) The clothing must be provided in a clean and dry condition at least weekly when airborne exposures are less than 200 $\mu\text{g}/\text{m}^3$ as an 8-hour TWA, or daily if exposures are greater than 200 $\mu\text{g}/\text{m}^3$.

(4) The employer is required to ensure that the protective clothing is removed at the completion of the work shift in appropriate change areas per paragraph (i) of OSHA 29 CFR 1926.62 lead standard; that clothing to be cleaned, laundered, or disposed of is placed in closed containers in the change area that prevents dispersion of lead outside the container; that lead is not removed from clothing or equipment by blowing, shaking, or other means that disperses the lead; and that persons who clean or launder the clothing are advised of the potential harmful effects of lead and the containers are labeled as follows: CAUTION: CLOTHING CONTAMINATED WITH LEAD. DO NOT REMOVE DUST BY BLOWING OR SHAKING. DISPOSE OF LEAD CONTAMINATED WASH WATER IN ACCORDANCE WITH APPLICABLE LOCAL, STATE, OR FEDERAL REGULATIONS.

f. Housekeeping.

(1) OSHA 29 CFR 1926.62 requires that all surfaces be maintained as free as practicable of accumulations of lead, and that floors and other surfaces where lead accumulates be cleaned, when possible, by vacuum or other methods that minimize the likelihood of the lead becoming airborne. Vacuums are to be equipped with HEPA filters. Only when these methods have been tried and been found to be ineffective can shoveling, dry or wet sweeping, or brushing be used. The OSHA standard prohibits the use of compressed air for removing lead from any surface unless it is used in conjunction with a ventilation system designed to capture the airborne dust created by the compressed air.

(2) The use of compressed air to blow-down surfaces within a ventilated containment would be acceptable if the ventilation system is adequate. However, the use of compressed air for housekeeping outside the ventilated containment is prohibited.

g. Hygiene facilities and practices. The employer must ensure that food or beverages are not present or consumed, tobacco products are not present or used, and cosmetics are

not applied within any areas where the lead exposure is above the PEL.

(1) Hand-washing facilities in accordance with paragraph (f) of OSHA 29 CFR 1926.51 must be provided for employees exposed to lead regardless of its concentration.

(2) Clean change areas must be provided for employees whose airborne exposure is above the PEL and for employees performing the tasks described in paragraph 11-3b(10) while the exposure monitoring is underway. The change areas must be equipped with storage facilities for protective work clothing and equipment that is separated from the storage of street clothes to prevent cross-contamination. Employees are not permitted to leave the work place wearing protective clothing or equipment that was worn during the work shift.

(3) Lunchroom facilities or eating areas are to be provided for employees with an airborne exposure to lead above the PEL, and the facilities or areas are to be maintained as free as practicable from lead contamination. Employees are required to wash their hands and face prior to eating, drinking, smoking, or applying cosmetics. Employees are not permitted to enter the lunchroom or eating areas wearing their protective work clothing or equipment unless the surface lead dust has been removed by vacuuming, downdraft booth, or other cleaning methods that limit its dispersion. Thus, the clothing need not be removed at lunch or for breaks if the surface dust has been thoroughly removed.

(4) Showers are required, where feasible, for use by employees with an airborne exposure to lead above the PEL. OSHA 29 CFR 1926.62 does not provide a definition of "feasible"; it states that, when shower facilities are available, employees must shower at the end of the work shift. If showers are not provided, employees must wash their hands and face at the end of the work shift. (Note: Because of the high dust and lead exposure generated during removal of lead paints by methods such as abrasive blast cleaning, showers are an important element in assuring proper hygiene.)

h. Medical surveillance.

(1) The medical surveillance provisions of OSHA 29 CFR 1926.62 consist of two parts, periodic biological (blood) monitoring and medical examinations. The employer must make all of the medical surveillance provisions available, but the OSHA standard does not require that the employee participate, although it is strongly recommended. All medical examinations and procedures

must be performed by or under the supervision of a licensed physician. All medical surveillance required by the OSHA standard must be made available to the employee (including multiple physician review), without cost to the employee and at a reasonable time and place.

(2) The biological monitoring consists of blood lead analysis and zinc protoporphyrin (ZPP). The blood lead level is assessed as micrograms of lead per deciliter of whole blood ($\mu\text{g}/\text{dl}$). These units are essentially equivalent to micrograms per 100 grams of blood. The ZPP test measures an adverse metabolite of lead, and as such it may be a better indicator of lead toxicity than the level of blood lead itself. The level of ZPP reflects lead absorption over the preceding 3 to 4 months, and it does not fluctuate over short time spans as blood lead levels do. Many investigators believe ZPP is the most reliable means of monitoring chronic lead absorption and that its value will increase as more data are collected regarding its relationship to other manifestations of lead poisoning.

(3) Initial medical surveillance must be made available to employees who are exposed on any day to lead at or above the action level. This surveillance consists only of the biological monitoring in the form of blood analysis for lead and ZPP.

(4) When employees are exposed to lead at or above the action level for more than 30 days in any consecutive 12 months, the medical surveillance program that must be made available consists of both the blood analysis per paragraph (j)(2) "Biological Monitoring" of OSHA 29 CFR 1926.62 and medical examinations per paragraph (j)(3) "Medical Examinations and Consultations" of the same standard.

(5) For each employee exposed at or above the action level for more than 30 days in any consecutive 12 months, the blood lead and ZPP level testing must be made available at the following frequency.

(a) At least every 2 months for the first 6 months of exposure, and every 6 months thereafter.

(b) For any employee whose analysis indicates a blood lead level at or above $40 \mu\text{g}/\text{dl}$, the test frequency is at least every 2 months. Testing continues at this 2-month frequency until two consecutive results indicate a blood level less than $40 \mu\text{g}/\text{dl}$, at which time the 6-month testing interval is resumed.

(c) For employees with a single blood lead level at or above $50 \mu\text{g}/\text{dl}$, a second test must be provided within 2 weeks after the results of the first test are received. If the

second test is at or above $50 \mu\text{g}/\text{dl}$, the worker must be removed from exposure to lead above the action level, the medical removal provisions of paragraph (k) of OSHA 29 CFR 1926.62 are invoked, and the sampling and analysis are undertaken at least monthly during the period of removal.

(6) Within 5 working days after receipt of the biological monitoring results, the employer must notify each employee in writing of the results. For employees with blood lead levels exceeding $40 \mu\text{g}/\text{dl}$, the notification also must advise the employee of the medical removal and protection provisions of OSHA 29 CFR 1926.62 as described in its paragraph (k) if their blood lead level increases to $50 \mu\text{g}/\text{dl}$.

(7) Medical examinations and consultations must be made available for employees exposed to lead at or above the action level for more than 30 days in any consecutive 12 months under the following conditions:

(a) Preassignment. The requirement for a preassignment medical examination is somewhat ambiguous in OSHA 29 CFR 1926.62, but the intent to require a preassignment examination is made clear in Appendix B of this standard.

(b) At least annually for each employee for whom a blood sampling test conducted at any time during the preceding 12 months indicated a blood lead level at or above $40 \mu\text{g}/\text{dl}$.

(c) As soon as possible on notification by an employee that signs or symptoms commonly associated with lead intoxication are occurring, that the employee desires medical advice concerning the effects of past or present lead exposure on the ability to procreate a healthy child, that the employee is pregnant, or if the employee has demonstrated difficulty in breathing during a respirator fitting test or during use of a respirator.

(d) As medically appropriate for each employee who has had limits placed on his or her lead exposure or has been removed from lead exposure as dictated by the medical removal protection provisions of paragraph (k) of OSHA 29 CFR 1926.62.

(8) The content of the medical examinations is at the discretion of the examining physician, but if requested by the employee, must include testing to determine if the employee is pregnant or laboratory evaluation of male fertility. The examination must include:

(a) A detailed work history and medical history, with particular attention to past lead exposure.

(b) A thorough physical examination, including an evaluation of pulmonary status if respiratory protection will be used.

(c) A blood pressure check.

(d) A blood sample and analysis that determines blood lead level, ZPP, hemoglobin, hematocrit, red cell indices, peripheral smear morphology, blood urea nitrogen, and serum creatinine.

(e) A routine urinalysis.

(f) Any other test relevant to lead exposure that the physician deems necessary.

(9) Physicians are to be provided with a copy of OSHA 29 CFR 1926.62 and all appendices, a description of the employee's duties, the employee's exposure level or anticipated exposure level to lead or other toxic substance (if applicable), a description of the personal protective equipment to be used, prior blood lead determinations, and all prior written medical opinions concerning the employee that are in the employer's possession or control.

(10) If the employer selects the initial physician, the employee may designate a second physician to review the findings and to conduct any examinations, consultations, and laboratory tests deemed necessary to facilitate the review. The employee shall be notified of this right to seek a second medical opinion. (The employer often requires notification within 15 days that a second opinion will be sought.) If the opinion of the two physicians differ and cannot be resolved, the employer and employee must designate a third physician to conduct a review. The employer must accept the findings of the third physician, unless the employer and employee reach an agreement that is consistent with the recommendations of at least one of the three physicians.

(11) The employee must be provided with a written copy of the medical opinion from each physician, including the physician's opinion about whether a medical condition was detected that would increase the risk of impairment to health because of exposure to lead, any recommended special protective measures needed or limitations to be placed on the employee's lead exposure, any recommended limitation on the use of respirators, and the results of blood lead determinations. Any findings, laboratory results, or diagnosis unrelated to the employee's occupational exposure to lead must not be revealed to the employer either in writing or orally.

(12) The employer must assure that prophylactic chelation (to reduce an existing high blood lead level or to prevent an elevation in blood lead) does not occur at any

time, unless it is done under the supervision of a licensed physician in a clinical setting. The employee also must be notified in writing prior to any treatment.

i. Medical removal protection.

(1) Employees must be removed from work involving an exposure to lead at or above the action level under the following conditions.

(a) When the results of a single blood test and a follow-up test, conducted within 2 weeks of receiving the results of the first test, are at or above 50 µg/dl. The employee may be returned to former job status when two consecutive blood tests indicate the blood lead level is at or below 40 µg/dl. (Blood tests are required at least monthly during the medical removal period.)

(b) When a final medical determination (written medical opinion by the examining physicians' or the outcome of multiple physicians review) results in a determination that the employee has a medical condition that if exposed to lead, increases the risk of material impairment to his or her health. The employee can be returned to former job status when a subsequent medical determination indicates that the detected medical condition no longer exists.

(2) An exception to removal based on the risk to health addressed in paragraph 11-3i(1)(b) above, can occur if the physician recommends special protective measures or limitations on the exposure to lead rather than the removal of the worker from lead exposure. In this situation the employer must act consistent with the recommendation. The special protective measures or limitations can be ended when a final medical determination indicates that the measures are no longer necessary.

(3) The requirement that the employee be returned to former job status after medical removal is not intended to expand on, or restrict, any rights the employee has or would have had to a specific job classification or position under the terms of a collective bargaining agreement. This significant point regarding worker medical removal protection is illustrated by the following example, which is found in the preamble to OSHA 29 CFR 1926.62: "... where an employee's job is concluded while the employee is on medical removal, the employee is not entitled to continuing medical removal protection benefits or to the job, since if the employee had not been removed, the employment would have ended in any case."

(4) On each occasion that the employee is removed from exposure to lead, the employer shall provide the employee with up to 18 months of medical removal protection

benefits. This means that, as long as the job the employee was removed from continues, the employer shall maintain the total normal earnings, seniority, and other employment rights and benefits of the employee, including the employee's right to his or her former job status as if the employee had not been removed or otherwise medically limited.

(5) If the removed employee files a claim for Workers' Compensation payments for lead-related disability, the employer still must continue to provide medical removal protection benefits pending disposition of the claim. If the employee is paid for lost earnings under Worker's Compensation during the period of removal, the employer's medical removal protection obligation under OSHA 29 CFR 1926.62 is reduced by that amount. The employer's financial obligation also is reduced by any compensation the employee receives for lost earnings either from a publicly or employer-funded compensation program, or if the employee receives income from other employment that was made possible because of the employee's removal from lead work.

(6) When an employer removes an employee from exposure to lead or otherwise places limitations on the employee because of the potential health effects of lead exposure, and does so voluntarily (i.e., was not required to do so as a result of elevated blood lead or a final medical determination), the medical removal protection benefits of OSHA 29 CFR 1926.62 still apply.

j. Employee information and training.

(1) All employees exposed to lead are to be trained on lead hazards in accordance with the requirements of OSHA 29 CFR 1926.59. Note: The OSHA Compliance Directive issued December 13, 1993, acknowledged that training in OSHA 29 CFR 1926.59 was not applicable to the lead standard because OSHA 29 CFR 1926.59 addresses materials brought onto the jobsite and would only apply if lead paint was being applied. For the removal of pre-existing paint, OSHA 29 CFR 1926.62 identifies the appropriate precautions. In addition, employees exposed to lead at or above the action level on any day, or who are exposed to lead compounds that may cause skin or eye irritation (e.g., lead arsenate, lead azide), must be provided with a comprehensive training program and required to participate. The lead training program must be given prior to the job assignment and repeated at least annually.

(2) The specific training program for lead exposure as required by OSHA 29 CFR 1926.62 must include the following:

(a) The content of OSHA 29 CFR 1926.62 and its appendices.

(b) The specific nature of the operations that could result in exposure to lead above the action level.

(c) The purpose, proper selection, fitting, use, and limitation of respirators.

(d) The purpose and explanation of the medical surveillance and medical removal protection programs.

(e) Information concerning the adverse health effects associated with excessive exposure to lead, with particular attention to the adverse effects on both male and female reproductive systems, as well as additional precautions for employees who are pregnant including hazards to the fetus.

(f) The engineering controls (e.g. ventilation inside containment) and work practices (e.g. proper hygiene) associated with the employee's job assignment including instructions to follow the good work practices that are described in Appendix B of OSHA 29 CFR 1926.62.

(g) The contents of any compliance plan in effect.

(h) Instructions to employees that chelating agents must not be used except under the direction of a licensed physician, and under no circumstance should they be used routinely for the removal of lead.

(i) The employee's right of access to records under OSHA 29 CFR 1910.20.

(3) A copy of OSHA 29 CFR 1926.62 and its appendices must be made available to all affected employees. Materials relating to employee information and training shall be provided upon request to employees, their designated representative, to the Assistant Secretary of OSHA and the Director of NIOSH.

k. Signs.

(1) The employer shall post warning signs in each work area where an employee's exposure to lead is above the PEL. The legend is as follows:

WARNING
LEAD WORK AREA
POISON
NO SMOKING OR EATING

(2) The warning signs must be illuminated and cleaned when necessary to assure that the words are visible. No statements are to be placed on or near any warning sign that contradict or detract from the meaning of the sign.

(3) Although not required by OSHA 29 CFR 1926.62, the area encompassed by the signs (the area in which the PEL is exceeded) may be isolated with rope or tape and termed a "regulated area." Untrained and unprotected personnel are not permitted to pass beyond the barrier. The regulated area is also often established at the boundary defined by the action level instead of the PEL, since the action level triggers that certain mandatory measures are required (e.g., blood lead analysis and training).

l. Recordkeeping. The employer is required to maintain a series of records on exposure assessments, medical surveillance, workers removed from lead exposure for medical reasons (medical removals), and any data used for requiring an exemption from the initial exposure monitoring required in paragraph (d) of OSHA 29 CFR 1926.62. The records include the following:

(1) Exposure assessment.

(a) All monitoring and other data used in conducting employee exposure assessments.

(b) The exposure monitoring records including the date(s) of monitoring, monitoring duration, location of the work monitored, and the results of each of the samples taken. If each employee was not individually monitored, the records must include a description of the procedure used to establish that the employees who were monitored were representative of the exposures of the other employees. The names, social security numbers, and job classifications of the employees monitored and of all other employees whose exposure the measurement is intended to represent must be provided. The sampling and analytical methods used, evidence of their accuracy, and the type of respiratory protective devices worn (if any) must be documented. Any environmental variables that could affect the measurement of employee exposure are to be included.

(c) The monitoring and other exposure assessment records are to be maintained in accordance with the provisions of OSHA 29 CFR 1910.20, which requires that employee exposure records be preserved and maintained for at least 30 years.

(2) Medical surveillance. Exceptions to the 30-year record retention period include health insurance claims records that are maintained separately, first aid records,

and medical records of employees who have worked for less than 1 year for the employer. Records for employees who have worked less than 1 year need not be retained beyond the term of employment if a copy is given to the employee on termination of employment.

(a) The employer is required to maintain accurate records for each employee subject to medical surveillance as required by paragraph (j) of OSHA 29 CFR 1926.62.

(b) The records must include the name, social security number, description of duties of the employee, and a copy of the physicians' written opinions. The results of any airborne exposure monitoring done on or for the employee that were provided to the physician must be included as well as any employee medical complaints related to exposure to lead.

(c) The employer must keep, or ensure that the examining physician keeps, a copy of the medical examination results, including the medical work history of the employee, a description of the laboratory procedures used, a copy of any standards or guidelines used to interpret the test results (or references to the information), and a copy of the results of the biological monitoring.

(d) The employer must maintain, or ensure that the physician maintains, the medical records in accordance with the provisions of OSHA 29 CFR 1910.20. OSHA 29 CFR 1926.62 requires that medical records for each employee be preserved and maintained for at least the duration of employment plus 30 years.

(3) Medical records.

(a) The employer must maintain accurate records for each employee removed from exposure to lead due to the requirements of paragraph (k) of OSHA 29 CFR 1926.62.

(b) The records must include the name and social security number of the employee, the date of each occasion the employee was removed from exposure to lead and the return date, a brief explanation of how each removal from exposure is being or was accomplished, and a statement indicating whether or not the removal from lead exposure was because of an elevated blood lead level.

(c) The employer must maintain each medical removal record for at least the duration of the employee's employment.

(4) Objective data for exemption from the requirement for initial exposure monitoring.

(a) Information demonstrating that a particular product or material containing lead (e.g. a particular paint), or a specific process, operation, or activity (e.g. hand-tool cleaning) cannot release lead dust or fumes in concentrations at or above the action level must be maintained if the data were used as the basis for an exemption from initial exposure monitoring. The objective data can be obtained from an industry-wide study, but the workplace conditions used during the study must closely resemble the processes, types of materials, control methods, work practices, and environmental conditions in the current operations they are intended to represent.

(b) The employer must maintain the record of the objective data for at least 30 years. All records must be made available on request to affected employees, former employees, their designated representatives, and the Assistant Secretary of OSHA and the Director of NIOSH for examination and copying. If an employer ceases to do business, the successor employer is required to receive and retain all records. When there is no successor employer, the records must be transmitted to the Director of NIOSH. When the retention period for the records expires, the employer must notify the Director of NIOSH at least 3 months prior to the disposal of the records and transmit them to the Director of NIOSH if requested. The employer also must comply with additional requirements involving transfer of records as set forth in OSHA 29 CFR 1910.20, paragraph (h) "Transfer of Records."

m. Observation of monitoring.

(1) Affected employees or their designated representatives must have the opportunity to observe any monitoring of employee exposure to lead. When the observation of monitoring requires entry into areas requiring the use of respirators, protective clothing, or equipment, the employer must provide the observer with the equipment and ensure that it is used; also, the observer is required to comply with all other applicable safety and health procedures.

(2) The observers are not permitted to interfere with the monitoring; but they are entitled to receive an explanation of the measurement procedures, to observe all steps related to the monitoring of lead, and to record the results obtained or receive copies of the results when they are returned by the laboratory.

11-4. Air Quality Regulations

a. National Ambient Air Quality Standards (NAAQS) for particulate matter. EPA 40 CFR 50.6 requires the measurement of particulate matter in the ambient air as

PM10 [particles with an aerodynamic diameter less than or equal to a nominal 10 micrometers (μm)]. Emissions cannot exceed $150 \mu\text{g}/\text{m}^3$, 24-hour average concentration. Another value, $50 \mu\text{g}/\text{m}^3$, annual arithmetic mean is also established in EPA 40 CFR 50.6. This type of monitoring is designed to protect against the inhalation of any particulate matter (not just lead or hazardous material) that is of a respirable size.

b. NAAQS for lead. Lead emissions are addressed in EPA 40 CFR 50.12. The criterion is $1.5 \mu\text{g}/\text{m}^3$, maximum arithmetic mean averaged over a calendar quarter. This assessment is based on an analysis of total suspended particulate (TSP) in the air.

c. Limitation and use of NAAQS on paint removal projects. Although ambient air quality standards for paint removal exist, they are not consistently imposed on paint removal projects. This type of standard usually is for the continuous, long-term monitoring of large areas (e.g., entire cities) as compared to individual short-term projects, and these standards are not designed for assessing emissions from a single source such as a dome. Despite the shortcomings, ambient air monitoring is being specified on some paint removal projects, and the NAAQS criterion (often with some modifications) is being invoked.

d. Air monitoring procedures.

(1) Monitoring may be initiated when there is a belief that emissions from a short-term paint removal project (particularly lead) could have an effect on the overall air quality in a region. Monitoring also may be imposed to better assure public health and welfare when the lead paint removal site is in a residential area or next to schools, hospitals, playgrounds, and other areas of public access. For work already underway, complaints over visible emissions or questions about the seriousness of emissions could be investigated with monitors. Prior litigation over emissions also may trigger monitoring on future projects. For example, monitoring has been required in Allegheny County, PA since 1987 for most abrasive blast-cleaning projects greater than 930 m^2 (10,000 sq ft) in area as a result of earlier litigation over silica contamination.

(2) The decision regarding whether to monitor a given project is not clear-cut. However, if there is a potential for public exposure to the dust, monitoring will provide a high degree of assurance that any emissions are within acceptable limits. Without monitoring, judgment calls are strictly subjective. For work within the confines of a plant when it can be established that dust and debris will not carry across the property line into a community, monitoring will provide little benefit. However, verification about the transport of

the dust and debris might require monitoring for a few days at project start-up. If the monitoring shows that the emissions do not carry into the community, facility owners might use only personal monitors (which determine worker exposures for OSHA purposes; see paragraph 11.3a) to establish a restricted or regulated area around the work site to avoid potential harm to other workers in the area.

e. Establishing daily criterion for air monitoring.

(1) Particulate matter.

(a) If NAAQS is appropriate for a given project, one difficulty in imposing its requirements is that the criterion for PM₁₀ is established on a 24-hour basis (rather than 8 hours or less, as is the typical duration of a paint removal operation). The SSPC guide GI(Con), "Guide for Containing Debris Generated During Paint Removal Operations," provides suggestions for converting the criterion to a daily value, but this guide cautions that local air quality officials should be contacted for approval.

(b) For PM₁₀ analysis, SSPC Guide GI(Con) suggests that 450 $\mu\text{g}/\text{m}^3$ over an 8-hour period may provide a rational method for applying the NAAQS criterion, if no emissions occur from the project site for the remaining 16 hours. This would be equivalent to 150 $\mu\text{g}/\text{m}^3$ for a 24-hour period.

(2) Lead. The NAAQS criterion for lead is 1.5 $\mu\text{g}/\text{m}^3$ based on a quarterly (90-day) average. SSPC guide GI(Con) suggests using two formulas for converting the quarterly average to a daily allowance based on the number of days out of 90 expected to be worked, and on the number of hours to be worked within a day. For example, if a project is expected to require 30 days of blast cleaning of the 90-day period, the first formula would permit 4.5 $\mu\text{g}/\text{m}^3$ of lead in each of the 30 days. If there are no emissions in the remaining 60 days, the average is 1.5 $\mu\text{g}/\text{m}^3$ for the quarter. If the blast cleaning involves 8 hours per day, the formulas would suggest a maximum allowable lead emission of 13.5 $\mu\text{g}/\text{m}^3$ for the 8-hour day if there are no emissions for the remaining 16 hours. The result is less than the maximum of 4.5 $\mu\text{g}/\text{m}^3$ for the day.

f. Placement of monitors.

(1) Guidance for positioning the monitors is found in Appendix E of EPA 40 CFR 58 where lead is addressed in item 7 and PM 10 is addressed in item 8.

(2) The approach used for monitor placement in Allegheny County, PA, has been reported by Sadar and Patel (1987). Information from this article and the CFRs

provides some guidance on monitor placement, but many lead paint removal projects are located over heavily travelled highways or near trees and other obstructions, and the ideal criteria for monitoring may be difficult to comply with in all situations. And, considerable judgment is required for the selection of placement sites. Wind speed and velocity; proximity to homes, neighborhoods, and areas of public access; and the effects of the surrounding terrain are only a few items to be considered. Therefore the value of any monitoring should be evaluated before it is specified.

g. Duration of monitoring.

(1) EPA 40 CFR 58.13 identifies the frequency of monitoring required (daily, every other day, etc.). EPA 40 CFR 58.13 is written for the long-term, continuous (permanent) monitoring at sites across the Nation to establish air quality data. As a result, there is no guidance on the duration of monitoring for short-term projects such as paint removal. However, industry experience shows the monitoring to follow one of four approaches:

(a) Continual monitoring throughout the entire project independent of the results (this would be the only acceptable method if strict compliance with the NAAQS is specified).

(b) Monitoring only when the work is in proximity to areas of public access (when the work is near a riverbank, but not while it is in the center of the river).

(c) Monitoring during the initial week or two of the project to establish the suitability of the methods used to control emissions; if acceptable, the frequency of monitoring is reduced or eliminated and resurrected only when problems appear to be occurring as determined by visual assessments.

(d) Monitoring only when complaints are received regarding visible emissions or questions are raised about the nature of the emissions.

h. Baseline monitoring. Adequate monitoring before a paint removal operation is undertaken will establish background levels. Depending on the variability of the results, continuous upwind, background monitoring may be required.

i. Volatile organic compounds (VOCs).

(1) Clean Air Act and Amendments.

(a) The Clean Air Act and the Clean Air Act Amendments of 1990 are affecting the coatings industry by restricting the amount of VOCs that can be emitted during

coating application (e.g., it impacts the solvents content allowed in the coating being applied).

(b) The portions of the Code of Federal Regulations addressing the Clean Air Act are found in 40 CFR Subchapter C "Air Programs" covering parts 40 CFR 50 through 40 CFR 99. The 1990 Amendments to the Clean Air Act can be obtained from Federal, state, or local EPAs.

(2) Definition of VOCs and cause for concern.

(a) VOCs are defined by the EPA as a group of chemicals that react in the atmosphere with nitrogen oxides in the presence of heat and sunlight to form ozone. Ozone in the lower atmosphere also is known as smog, a pollutant detrimental to plants and humans. The National Air Quality Standard for ozone is found in EPA 40 CFR 50.9, which establishes a level of 0.12 ppm maximum hourly average concentration. Areas that exceed this level more than once per year are termed nonattainment areas, with further classification as marginal, moderate, serious, severe, and extreme (e.g., extreme is far above the limit at 0.28 ppm and greater). A city or area has a certain number of years (ranging from 3 to 20) to bring the ozone level into compliance. The higher the existing level (e.g., extreme), the longer the time period for compliance.

(b) Because emissions from coatings (solvents in particular) can contribute to the formation of ozone in the lower atmosphere, the EPA has been directed to regulate VOCs. In the 1970's, the EPA issued control technique guidelines (CTG) for VOCs in coatings for miscellaneous metal parts. The CTG apply to nonattainment areas and are intended to provide guidance for the state and local agencies on VOC emissions from fabricating shops and other fixed-facility operations. Although the CTG are for guidance only, state and local agencies must develop rules that are at least as strict as those found in the CTG.

(3) Variance in VOC restrictions.

(a) The restrictions on VOCs per gallon of paint vary according to the category of coating and its usage, but maximums generally range from 340 grams per liter (g/L) (2.8 pounds/gallon [lb/gal]) to 420 g/L (3.5 lb/gal). In some jurisdictions, there are exemptions for specific types of coatings or for coatings used for specific applications in which higher VOC levels are allowed. There also is work underway to further reduce the level of VOCs in all coatings.

(b) A national VOC rule on Architectural and Industrial Maintenance (AIM) coating applied to stationary sources is being developed. Under a tentative agreement, industrial

maintenance coating would be restricted to a maximum of 350 g/L (2.9 lb/gal) as applied. Tentative levels also have been established for approximately 50 other categories and subcategories of coating. The national rule as currently envisioned would become increasingly more restrictive in 1996, 2000, and 2003. Reduction is scheduled for 25 percent by 1996, 35 percent by 2000, and 45 percent by 2003.

(4) VOC as manufactured versus "as applied." When investigating acceptable coatings, the VOC "as applied" counts rather than the VOC "in the can." For example, a solvent-based coating containing 340 g/L (2.8 lb/gal) VOC in the can that must be thinned 10 percent for application will exceed the 340 g/L (2.8 lb/gal) threshold at the time of application. If the local regulations restrict the use of materials to those containing 340 g/L (2.8 lb/gal) or less, the coating given in the example could not be used.

(5) Other coating restrictions. In addition to restrictions associated with VOC, precaution must be taken when using other materials that may be hazardous to humans. Pigments that can be toxic include lead, chromium, barium, cadmium, mercury, and others as described in paragraph 11-7. Almost all paint manufacturers have removed toxic pigments such as lead from their products, and many good alternatives are available. Some solvents used in paints, such as ethylene glycol ethers, also are being avoided because of toxicity. MSDS for all candidate paint materials should be thoroughly reviewed before specifying a product. The American Industrial Hygiene Association can provide information on the potential health effects of various elements and solvents.

11-5. Water Quality Regulations

a. *40 CFR Subparts D, Parts 100-149.* The portions of the Code of Federal Regulations that address the Clean Water Act are found in 40 CFR Subchapter D "Water Programs" and encompass Parts 100 through 149. EPA 40 CFR 116 lists substances that are designated as being hazardous under the Clean Water Act.

b. *Reportable quantities.* The reportable quantities of hazardous substances that would result in a violation of the Clean Water Act are found in EPA 40 CFR 117, Table 117.3, "Reportable Quantities of Hazardous Substances Designated Pursuant to Section 311 of the Clean Water Act." Table 117.3 indicates the maximum amount of the substance that can be discharged in a 24-hour period. In the case of the various forms of lead listed in the table, the reportable quantities range from 0.453 to 2,265 kilograms (kg) (1 to 5,000 lb) over a 24-hour period. The type of lead found in paint is not specifically listed in Table 117.3, but a reportable quantity of lead (which would

include paint pigments) under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) is 10 lb (4.5 kg) in a 24-hour period. CERCLA reporting is addressed in paragraph 11.7a(3). EPA 40 CFR 117.21 requires the immediate notification of the appropriate agency of the U.S. Government when a discharge equal to or exceeding the reportable quantity occurs in any 24-hour period.

c. Permits.

(1) EPA 40 CFR 122 "EPA Administered Permit Program: The National Pollutant Discharge Elimination System" requires in Section 122.1 "Purpose and Scope" that permits must be obtained for the discharge of a pollutant from any point source into waters of the United States. "Discharge" essentially indicates a channeled discharge. Accordingly, unless there is an intent to channel or discharge the paint debris into waters of the United States, it is questionable whether the NPDES permit is required. Conversely, if the intent is to allow the debris to fall into the water, a permit to allow this probably would not be issued. For example, shipyards cannot allow debris to fall into the water.

(2) If a permit is required, obtaining one requires 90 days. The Government or general contractor is responsible for obtaining the permit.

d. No allowable release(s). Independent of any interpretations applied to the regulations, paint debris containing lead or other hazardous materials cannot be discharged into the water or be located in an area where it could be carried into a storm sewer; this statement is based on the requirements of 40 CFR 122.26, "Storm Water Discharges." The emission and debris must be controlled.

11-6. Soil Quality Requirements

a. OSWER Directive #9355.4-02.

(1) The Code of Federal Regulations does not address the contamination of soil resulting from lead paint removal projects. However, state and local laws and regulations may provide controls over soil contamination and should be investigated before initiating a project. Although not associated with lead paint removal at this time, the USEPA Office of Solid Waste and Emergency Response (OSWER) provides guidance on cleanup levels for total lead in soil at Superfund sites, which are locations where hazardous waste is "discovered" and must be cleaned up before the property can be used.

(2) OSWER Directive #9355.4-02 "Interim Guidance on

Establishing Soil Lead Clean-Up Levels at Superfund Sites," dated September 7, 1989, establishes cleanup at total lead levels of 500 to 1,000 ppm when the current or predicted use of the land is residential. The directive states that further guidance on cleanup levels will be developed after the USEPA conducts additional studies. Some states have established their own soil cleanup standards that are more restrictive (e.g., New Jersey at 100 ppm), and a Canadian province (Ontario) established cleanup guidelines for lead in soil dependent upon land use (i.e., agricultural, 60 ppm; residential/parkland, 500 ppm; commercial/industrial, 1,000 ppm).

b. Pre- and post-job soil sample analysis. Despite the lack of guidance on permissible lead soil contamination for paint removal projects, some owners have the lead in soil analyzed prior to project start-up and on completion. Unfortunately, without definitive guidance on the levels of lead from paint removal projects that are harmful, firm specification requirements on allowable increases are difficult to develop. Specifications have been written in private industry to stipulate that no increase in the soil lead level should be observed on project completion; others allow an increase up to a certain percentage. However, specifications that demand a 0 percent increase in soil lead levels do not allow for variability in the methods used for sampling and analysis, and thus can be unattainable. Also, specifications that permit a given increase to occur (e.g., 10 percent) may be unattainable if the original soil contains little to no lead. Allowing an increase of a certain amount (e.g., 100 ppm) of total lead regardless of the initial level may provide a compromise position.

c. Sampling and analysis. Site-specific factors must be considered by the project designer in the final site selection criteria. For instance, the number of sampling locations along the structure and the distance away from the structure depend on such factors as the height and length of the structure, wind conditions, obstacles, and the topography of the land.

(1) The project is divided into "unique structures." For example, each water or fuel storage tank, even if it is a part of a large tank farm, is considered to be a unique structure. For bridge projects, each segment of the bridge between support piers is considered to be a unique structure. For buildings, each building, regardless of its size, is considered to be a unique structure.

(2) If the structure crosses soil (either the ground below or the banks of a river or shoreline), a minimum of two samples are taken at locations spaced equidistant from each end or side and directly beneath the center of each unique structure, if appropriate. The number of sampling locations

beneath the structure usually is increased in proportion to the "floor area" of the structure. For example, one additional sample might be removed for every 465 m² (5,000 sq ft) of ground surface covered.

(3) An additional series of samples should be considered around the structure on each side (north, south, east, and west) in which soil is present:

(a) If the structure is less than 15.25 m (50 ft) in height, the samples should be removed at a distance away from the structure roughly equivalent to its height. For long structures, one sample location should be selected for every 30.5 m (100 lineal feet).

(b) For structures more than 15.25 m (50 ft) in height, two rows of sample locations should be selected along each side. The first row should be located within 15.25 m (50 ft) of the structure and the second at a distance approximately one times the height of the structure. One sample in each row should be selected for every 30.5 m (100 lineal feet) of structure.

(4) If high-risk receptors (e.g., schools, day-care centers, occupied housing, hospitals) are located close to the work area, soil samples should be removed at each high-risk receptor location.

(5) Additional surface and subsurface soil sampling, soil hydrology studies, and other aspects of an environmental site characterization study may be necessary to properly assess the need (and magnitude) for remediation if soil contamination is identified during postproject soil sampling.

d. Sampling and analysis procedures.

(1) Measure and record the specific location of each of the sites. The documentation must be sufficiently accurate to allow a technician to return to the precise location when the project is completed.

(2) At each site, center and align a 0.093 m² (1 sq ft) template parallel or tangential to the structure.

(3) Remove a sample of soil 19 mm (3/4 in.) in diameter and 12.7 mm (1/2 in.) deep at the center of the template and at each of the four corners. Place each of the five plugs in a single bag. This represents the sample at the specific location.

(4) Seal each bag and record the date of testing, specific location, name of technician removing the sample, names of others present, and signatures.

(5) Enter the sample information into a log book, and record the laboratory to which the samples are sent for testing and the date of shipment.

(6) The samples must be analyzed in accordance with USEPA method 3050, Acid Digestion of Sediments, Sludge, and Soils, or a USEPA-approved equivalent method.

(7) When the results are received from the laboratory, enter them into the log book.

(8) When the project is completed, return to the precise locations and repeat the sampling process.

e. Remediation. The contractor should be required to return the soil to background levels if an unacceptable increase (e.g., 100 ppm) is discovered.

11-7. Handling, Storage, and Disposal of Hazardous Waste

a. Regulations.

(1) RCRA.

(a) The Resource Conservation and Recovery Act (RCRA) was issued in 1976; its regulations are found in 40 CFR 240 through 280. RCRA added provisions to the previous Solid Waste Act pertaining to hazardous waste management by establishing the following goals: to protect human health and the environment, to reduce waste and conserve energy and natural resources, and to reduce or eliminate the generation of hazardous waste as expeditiously as possible.

(b) RCRA is divided into 10 subtitles labeled A through J. Regulations regarding hazardous waste are in Subtitle C "Hazardous Waste Management." Hazardous waste is regulated under RCRA if more than 100 kg (220 lb) are generated each month; this should encompass most lead paint removal projects. If less than 100 kg (220 lb) of waste are generated, the detailed RCRA documentation requirements do not apply, but the generator must assure proper disposal. However, disposal sites may require an identification number before accepting the waste.

(c) The purpose of Subtitle C is to establish a system for controlling hazardous waste from its generation ("cradle") to its ultimate disposal ("grave"). Thus, the coined phrase "cradle-to-grave."

(d) The RCRA Subtitle C rules identify three regulated activities: generators of hazardous waste, transporters of

hazardous waste, and owners or operators of hazardous waste treatment, storage, or disposal facilities.

(e) The USACE is the generator of the waste and therefore is responsible for its proper handling and disposal, even if a contractor is hired to test, handle, store, and arrange for the waste transportation and disposal.

(2) RCRA land disposal restriction treatments and standards. Since enactment of the Land Disposal Restrictions in August 1990, hazardous lead paint debris may no longer be land disposed unless it is further treated to render it nonhazardous. Treatment typically involves mixing the debris with cement-like material at the disposal facility. However, additives can be combined with the abrasive prior to use that may render the debris nonhazardous at the point of generation. Research is being conducted to determine whether these additives provide long-term stabilization.

(3) CERCLA.

(a) Although the management of hazardous waste from cradle-to-grave is addressed by RCRA, RCRA does not address the cleanup of existing sites containing hazardous waste, nor does it address releases or spills of hazardous substances. These problems are addressed by CERCLA, commonly called Superfund. CERCLA was enacted in 1980 both to remedy current releases of hazardous substances and to address the cleanup of sites in which hazardous waste is found. CERCLA originally was authorized for 5 years, but in 1986 it was amended by the Superfund Amendments and Re-Authorization Act (SARA). SARA extended the time frame of CERCLA and increased the funding from \$1.6 billion to \$8.5 billion. SARA also included provisions for public education, emergency planning, and the notification of state and local authorities if releases of certain chemicals occur. This is found in SARA Title III, the Emergency Planning and Community Right-To-Know Act, which was enacted in reaction to the toxic chemical release in Bhopal, India.

(b) The CERCLA and SARA requirements are addressed in 40 CFR Subchapter J, "Superfund, Emergency Planning and Community Right-To-Know Programs," covering Parts 300 through 373.

(c) A CERCLA release must be reported if lead paint, dust, and debris escape the work area into the environment (i.e., ambient air, water, soil) in the quantities identified under 40 CFR 302, "Designation, Reportable Quantities, and Notification." Lead is listed in 40 CFR 302 with a reportable quantity of 10 lb (4.5 kg) in a 24-hour period. The total square feet of paint that might generate a CERCLA response if removed by blast cleaning without

containment will vary depending on the initial lead content and thickness of the paint, but it could be less than 100 sq ft (0.09 sq m).

b. Definition and testing of hazardous waste.

(1) Hazardous waste characteristics. A hazardous waste is garbage, sludge, solid, or semisolid that is discarded and determined to be a threat to health or the environment by exhibiting any of the following characteristics: ignitability (assigned the USEPA hazardous waste number of D001), corrosivity (assigned the USEPA hazardous waste number of D002), reactivity (assigned the USEPA hazardous waste number of D003), toxicity (assigned a variety of unique USEPA numbers beginning with D004; lead is D008).

(2) Unused coating (ignitability). Unused paint may be considered hazardous because of ignitability and, depending on its constituents, toxicity.

(3) Heavy metals concentration (levels).

(a) Debris generated during paint removal is classified as hazardous because of toxicity if the amount of toxic material leached or extracted from the debris using the toxicity characteristic leaching procedure (TCLP) exceeds a certain threshold.

(b) The leachable levels that classify debris as hazardous because of toxicity are listed in Table 11-2. The results in Table 11-2 can also be given in parts per million (e.g., 5 mg/L = 5 ppm). The metals typically of concern in paint are lead, chromium, barium, cadmium, and mercury.

Table 11-2
Leachable Levels That Result in Toxicity

Metal	Concentration, mg/L
Arsenic	5.0
Barium	100.0
Cadmium	1.0
Chromium	5.0
Lead	5.0
Mercury	0.2
Selenium	1.0
Silver	5.0

(4) Toxicity characteristic leachable procedure.

(a) Sample collection. Collection of the samples for

testing typically requires the use of simple random sampling, with a minimum of four samples required from each waste stream. Sampling should represent the entire waste stream from single job (for small projects), or a sample may be removed daily, weekly, or at some other frequency. The use of a statistician in developing sampling plans can be helpful.

(b) Test procedure. The TCLP is outlined in Appendix II of EPA 40 CFR 261. A minimum sample size of 100 grams (g) is required for each test. An acid solution is prepared as the extraction fluid; this fluid is combined with the waste using specialized procedures and placed in an extraction vessel that tumbles end-over-end for 18 hours. The liquid is analyzed at the end of the extraction for heavy metals using atomic absorption spectroscopy or inductively coupled plasma-atomic emission spectroscopy.

c. Generator requirements.

(1) For paint removal, the generator of the waste is typically the owner of the facility. If the volume of the debris is greater than 100 kg (220 lb) per month, the generator must comply with all of the regulations for generators found in EPA 40 CFR 262 and the many parts referenced. A conditionally exempt small quantity generator (less than 220 lb) need not comply with the detailed EPA 40 CFR 262 regulations but must ensure that the waste is properly disposed of or recycled.

(2) A summary of the requirements for the small- and large-quantity generators according to RCRA follows. A large-quantity generator generates over 1,000 kg (2,200 lb) of hazardous waste per month, or stores more than 6,000 kg (13,200 lb) of waste at the site at any one time. A small-quantity generator generates more than 100 kg (220 lb) but less than 1,000 kg (2,200 lb), of hazardous waste per month, and accumulates less than 6,000 kg (13,200 lb) at any one time.

(a) Identification of waste. EPA 40 CFR 262.11 requires that the generator determine if the waste is hazardous. This is accomplished by applying knowledge of the hazardous characteristics of the material in light of the process used, or through laboratory testing. The laboratory testing is intended to simulate the type of long-term leaching that could occur in sanitary landfills. If the leaching lead paint debris exceeds the allowable levels given here the debris is considered to be hazardous because of toxicity.

(b) USEPA identification number (40 CFR 262.12). The generator must obtain an identification number to treat, store, dispose of, transport, or offer for transportation, the hazardous waste.

(c) Notification and certification (40 CFR 268.7 and 40 CFR 268.9). A notification and certification must be provided by the generator and treatment facility for each shipment of debris. The specific wording is found in the regulations and varies according to whether the restricted waste tests hazardous or tests nonhazardous, or has been treated to render it nonhazardous. Information required can range from an identification of the treatment standards that should be used for the debris, to certifications about the personal knowledge of the waste, treatment process, and test results. False certification can result in a fine and/or imprisonment.

(d) Manifesting the waste (40 CFR 262.20 through 262.23). The generator must complete a hazardous waste manifest that accompanies each shipment. The manifest includes a description of the waste, the name of the facility permitted to handle the waste, and an alternate facility. The generator signs the manifest as does each transporter and the final disposal facility. The completed manifest must be returned to the generator within a designated number of days (45 days for large-quantity generator and 60 days for small-quantity generator). If the manifest is not received, the manifest and debris must be tracked and located. The manifest assures that the waste is properly handled from the collection of the debris to its final disposal.

(e) Packaging and labeling requirements (40 CFR 262.30 through 262.33). The waste must be packaged in accordance with the requirements of the 40 CFR 262 sections given here and Department of Transportation Regulations presented in 49 CFR 173, 178, and 179, with labeling accomplished in accordance with 49 CFR 172. Essentially, 49 CFR 172, 173, 178, and 179 require that the packaging be capable of preventing leakage of the waste during normal transportation conditions and upset conditions (e.g., container falling out of a truck), and require the use of labels, marking, or placards to identify the characteristics or dangers associated with transporting the waste. The labels must identify the contents, tare weights of the containers, origin of the material, and the date.

(f) Container enclosure requirements (40 CFR 265). The requirements vary between the large- and small-quantity generator, but both essentially require the use of leakproof drums or bins with secure lids or covers for containing the material, with the storage site locked and located on well drained ground. The containers must be inspected for corrosion and leaking.

(g) Contingency plan and training (40 CFR 265 and 40 CFR 262.34). Personnel involved with the handling of hazardous waste must be trained to respond effectively to emergencies; this also includes paint removal crews. Basic

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safety information must be available, including hazardous labels on containers, the date the accumulation first begins, the name and telephone number of a site employee who is the emergency coordinator, the telephone number of the fire department, the location of the fire extinguisher, and other similar contingency items.

(h) Waste analysis plans for onsite treatment (40 CFR 268.7). If the generator decides to treat the waste onsite to render it nonhazardous, a written waste analysis plan must be filed with the USEPA regional administrator a minimum of 30 days prior to the treatment activity.

(i) Waste accumulation time (40 CFR 262.34). There are restrictions on the length of time that the waste may accumulate onsite. A large-quantity generator may

accumulate the hazardous waste onsite for 90 days or less without a permit, with an extension of up to 30 days possible because of unforeseen, temporary, or uncontrollable circumstances. A small-quantity generator may accumulate waste onsite for 180 days, with a possible exemption permitting up to 270 days. If these time limits are exceeded, the generator may be considered to be an operator of a storage facility and would be subject to other extensive requirements.

(j) Recordkeeping and reporting (40 CFR 262.40 through 262.44). The signed manifests and associated documentation must be maintained for at least 3 years. For generators who treat the waste onsite, the recordkeeping requirements can be more elaborate.

Appendix A References

A-1. Required Publications

Section I

Code of Federal Regulations (CFR)

Title 29 "Labor" contains Office of Safety and Health Administration (OSHA) standards. Title 40 "Protection of the Environment" contains U.S. Environmental Protection Agency (EPA) standards. Copies of CFRs may be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

OSHA 29 CFR 1910.106

Safety and Health Rules for General Industry

OSHA 29 CFR 1910.133

Eye and Face Protection

OSHA 29 CFR 1910.134

Requirements for a Minimal Acceptable Program

OSHA 29 CFR 1910.146

Permit-Required Confined Spaces

OSHA 29 CFR 1910.20

Access to Employee Exposure and Medical Records

OSHA 29 CFR 1926.103

Respiratory Protection

OSHA 29 CFR 1926.152

Construction Industry Standard

OSHA 29 CFR 1926.16

Rules of Construction

OSHA 29 CFR 1926.21

Safety Training and Education

OSHA 29 CFR 1926.302

Power-Operated Hand Tools

OSHA 29 CFR 1926.354

Welding, Cutting, and Heating in Way of Preservative Coatings

OSHA 29 CFR 1926.51

Sanitation

OSHA 29 CFR 1926.59

Hazard Communication Standard

OSHA 29 CFR 1926.62

Lead

OSHA 6-9

Construction Lead Standard

OSWAR Directive 9355.4-02

Interim Guidance on Establishing Soil Lead Clean-Up Levels at Superfund Sites

EPA 40 CFR 50.6

National Primary and Secondary Ambient Air Quality Standards for Particulate Matter

EPA 40 CFR 50.9

National Primary and Secondary Ambient Air Quality Standards for Ozone

EPA 40 CFR 50.12

National Primary and Secondary Ambient Air Quality Standards for OSHA, Lead

EPA 40 CFR 58

Probe Siting Criteria for Ambient Air Quality Monitoring

EPA 40 CFR 58.13

Operating Schedule

EPA 40 CFR 116

Designation of Hazardous Substances

EPA 40 CFR 117

Table 117.3, Reportable Quantities of Hazardous Substances Designated Pursuant to Section 311 of the Clean Water Act, and 117.21, Notice

EPA 40 CFR 122

Administered Permit Program: The National Pollutant Discharge Elimination System

EPA 40 CFR 261

Identification and Listing of Hazardous Waste

EPA 40 CFR 262

Standards Applicable to Generators of Hazardous Wastes

EPA 40 CFR 265

Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities

EM 1110-2-3400

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EPA 40 CFR 268

Land Disposal Restrictions

48 CFR 1-10.002

Federal Acquisition Regulation - Specifications, Standards, and Other Purchase Descriptions

48 CFR 1-13.106

Federal Acquisition Regulation - Small Purchase and Other Purchase Procedures

49 CFR 172

Transportation: Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, and Training Requirements

49 CFR 173

Transportation: Shippers - General Requirements for Shipments and Packagings

49 CFR 178

Transportation: Specifications for Packagings

49 CFR 179

Transportation: Specifications for Tank Cars

EPA Method 3050

Acid Digestion of Sediment, Sludge, and Soils

SW-846 Method 6010

USEPA Manual

SW-846 Method 7420

USEPA Manual

SW-846 Method 7421

USEPA Manual

Section II

Federal Agencies

DOD-E-18210B

Enamel, Interior, Deck, Red (Formula No. 23) (Metric)

DOD-P-15328

Primer (WASH) Pretreatment (Formula No. 117 for Metals)

MIL-C-18480A(3)

Coating Compound, Bituminous, Solvent, Coal Tar Base

MIL-C-83286B

Coating, Urethane, Aliphatic Isocyanate, for Aerospace Applications

MIL-P-14105C

Paint, Heat Resisting, (for Steel Surfaces)

MIL-P-24441A

Paint, Epoxy-polyamide, General Specifications for

Fed Spec TT-P-28

Paint, Aluminum, Heat Resisting (1200 °F)

Fed Spec TT-V-109

Varnish, Interior, Alkyd-Resin

Fed Spec TT-E-489

Enamel, Semigloss, Rust-Inhibiting

Fed Spec TT-E-496

Enamel: Heat Resisting (400 °F), Black

Fed Spec TT-E-529

Enamel, Alkyd, Semigloss

Fed Spec TT-V-1593

Enamel, Silicone Alkyd Copolymer Gloss (for Exterior and Interior Use)

Federal Standard 595

Colors Vol. 1

Federal Test Method 6221

Flexibility

Federal Test Method Standard (FTMS) 141C

Paint, Varnish, Lacquer, and Related Materials; Methods for Sampling and Testing

TM 5-811-7

Electrical Design, Cathodic Protection

ER 700-1-1

USACE Supply Policies and Procedures

ER 1110-2-1200

Plans and Specifications for Civil Works Projects

ER 1125-2-303

Design, Acquisition and Construction

EM 385-1-1

Safety and Health Requirements

EM 1110-2-3105

Mechanical and Electrical Design of Pumping Stations

ETL 1110-3-440

Cathodic Protection

ETL 1110-9-10

Cathodic Protection Systems Using Ceramic Anodes

CEGS 09900

Painting, General

CWGS 05036

Metallizing: Hydraulic Structures

CWGS 09940

Special Paints Formulations Section

CWGS 16643

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Appendix B

Glossary

AAS	atomic absorption spectroscopy	km	kilometer
ACGIH	American Conference of Governmental Industrial Hygienists	kPa	kiloPascal
AIHA	American Industrial Hygiene Association	lb	pound
AIM	Architectural and Industrial Maintenance	lb/gal	pounds per gallon
ANSI	American National Standards Institute	LEL	lower explosive limit
ASME	American Society of Mechanical Engineers	MAS	Multiple Award Schedule
ASTM	American Society for Testing and Materials	MDI	4,4'diphenylmethane diisocyanate
AWWA	American Waterworks Association	MEK	methyl ethyl ketone
CENCR	Rock Island District	mg/cm ²	milligrams per square centimeter
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act	mg/L	milligrams per liter
cfm	cubic feet per minute	µg/cm ²	micrograms per square centimeter
CFR	Code of Federal Regulations	µg/m ³	micrograms per cubic meter
CIH	certified industrial hygienist	µg/L	micrograms per liter
CP	cathodic protection	µm	micrometer
CPVC	chlorinated polyvinyl chloride	mm	millimeter
CTE	coal tar epoxy	mph	miles per hour
CTG	control technique guidelines	MSDS	material safety data sheets
DC	direct current	MSHA	Mine Safety and Health Administration
DFT	dry film thickness	mV	millivolts
DTM	direct to metal	MVP	moisture vapor permeability
EPA	Environmental Protection Agency	NAAQS	National Ambient Air Quality Standards
EPDM	ethylene propylene diamine monomer	NACE	National Association of Corrosion Engineers
FAA	Federal Aviation Administration	NASA	National Aeronautic Space Administration
FDA	Food and Drug Administration	NFPA	National Fire Protection Association
Fe	iron	NIOSH	National Institute for Occupational Safety and Health
fpm	feet per minute	NPDES	National Pollutant Discharge Elimination
fps	feet per second	NSF	National Sanitation Foundation
FRP	fiberglass-reinforced plastic	OSHA	Occupational Safety and Health Administration
FSS	Federal Supply Schedule	OSWER	Office of Solid Waste and Emergency Response
FTMS	Federal Test Method Standard	PDCA	Painting and Decorating Contractors of America
g	grams	PEL	permissible exposure limit
g/L	grams per liter	PM 10	particulate matter with an aerodynamic diameter less than or equal to a nominal 10 micro- meters (microns)
GSA	Government Services Administration	ppb	parts per billion
HDI	1,6' hexamethylene diisocyanate	ppm	parts per million
HEPA	high efficiency particulate air	psi	pounds per square inch
HMPE	high molecular weight polyethylene	PVA	polyvinyl acetate
HVLP	high volume-low pressure	PVC	polyvinyl chloride
ICP-AES	inductive coupled plasma atomic emission spectrometry	QPL	Qualified Products List
i.d.	inside diameter	RCRA	Resource Conservation and Recovery Act
in.	inch	RP	recommended practices
kg	kilogram		

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SARA	Superfund Amendments and Re-Authorization Act	USACE	U.S. Army Corps of Engineers
SCBA	self-contained breathing apparatus	USACERL	U.S. Army Corps of Engineers Construction Engineer Research Laboratories
sq ft	square foot	USEPA	U.S. Environmental Protection Agency
SSPC	Steel Structures Painting Council	UV	ultraviolet
TCLP	toxicity characteristic leaching procedure	V	volt
TDI	toluene diisocyanate	VOC	volatile organic compound
TSP	total suspended particulate	XRF	x-ray fluorescence
TWA	time weighted average	ZPP	zinc protoporphyrin
UEL	upper explosive limit		

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